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Fundamental Heat Transfer Research for Gas Turbine Engines

A workshop held at the
NASA Lewis Research Center
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Mechanical and Energy Systems Engineering Department
Arizona State University
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FOREWORD

The Heat Transfer Fundamentals Section of the Turbine Branch, Aerothermodynamics and Fuels Division, organized a two-day workshop at the Lewis Research Center on Fundamental Heat Transfer Research for Gas Turbine Engines. The purpose of the meeting was to assemble experts from industry, universities, and government who are working in gas turbine heat transfer research to discuss needed research and recommend approaches to be incorporated into the Center's research plan for gas turbine heat transfer fundamentals.

The response to invitations to participate was excellent, and 37 persons from industry and the universities joined some 24 Lewis staff members in an intense exchange of ideas. Professor Darryl E. Metzger of Arizona State University was the general chairman of the workshop.

The meeting agenda was structured to provide maximum interactions between the outside attendees and the Lewis staff. The primary format was small working groups in roundtable discussions. Only about 20 percent of the agenda time was devoted to presentations of current research by the Lewis staff.

This report, prepared by Professor Metzger, presents a summary of the workshop. It includes pre-workshop input from the participants, presentations of current activity by the Lewis staff, reports of the four working groups, and a summary prepared by Professor Metzger. It is the hope of the organizers that the workshop and this report have formed a dynamic beginning to a continuing dialog between industry, universities, and government on important questions of fundamental research in gas turbine heat transfer.

Robert J. Simoneau
Workshop Organizer

CONTENTS

INTRODUCTION AND ORGANIZATION

The Workshop on Fundamental Heat Transfer Research for Gas Turbine Engines was organized to accomplish several objectives. First, to provide a common meeting ground and forum for discussions among practitioners from all the segments of the technology: industry, government, and universities. Second, to uncover industry-wide problem areas where heat transfer research can contribute to product improvement, and to discuss priorities and strategies for attacks on these problems. Third, to provide a forum for presentation of current and planned NASA work and description of NASA facilities. And fourth, to provide an opportunity for collective industry and university input to NASA planning.

In terms of the first two objectives, this meeting is the third in a series of recent gatherings of workers in gas turbine heat transfer. The first of these, sponsored by the Office of Naval Research, was held at the Naval Postgraduate School, Monterey, California, in September 1978. The second, sponsored by ASME, was a session at the 1980 Gas Turbine Conference at New Orleans, Louisiana, in March 1980.

The continuing active interest in meetings to discuss common problems and possible approaches in gas turbine heat transfer research underscores the important role heat transfer plays in the continued development of these engines, in terms of both improved performance and improved durability. It is also indicative of the overall complexity of fluid mechanic and convective heat transfer phenomena in turbomachinery; and the necessity, as continued improvement is sought, to recognize and deal with more and more of these complexities.

The Workshop organizers attempted to give the two-day meeting some initial momentum by requesting advance input from the participants in the form of written goals and identification of problem areas. This pre-workshop input was assembled and distributed to all participants in advance of the meeting. It is also reproduced in this report, largely unedited, as an essentially independent resource.

The morning of the first workshop day was devoted to presentations of NASA Lewis current programs and plans by various NASA personnel. The first afternoon and second morning were mainly devoted to working group deliberations, with working group reports and open discussion occupying the second afternoon.

The working groups were organized along the lines of methods of attack, experimental and analytical, rather than around specific problem areas. Based partially on the pre-workshop input, and on the number of expected attendees, four workshop groups were planned: two in Near Engine Environment Experiments, and one each in Computational Analysis and Basic Experiments. Robert Fish of Pratt and Whitney Aircraft and David Nealy of Detroit Diesel Allison chaired the near engine experiments groups. Richard Pletcher of Iowa State University and Robert Mayle of Rensselaer Polytechnic Institute chaired the computation and basic experiments groups, respectively. The organizers are deeply indebted to these individuals for accepting and carrying out the most difficult assignments of the meeting.

The sections that follow present the Workshop results in essentially chronological order from pre-workshop input through the NASA Lewis presentations to the final workshop group reports. The final section is an editorial summary covering both the formal group reports and impressions derived from transcripts of the group deliberations and final discussions. A complete listing of names and addresses of all participants is included as Appendix A.

PRE-WORKSHOP INPUT FROM PARTICIPANTS

Participants were asked to provide the workshop organizers with written input in advance of the meeting. Both goals for their work over the next few years and suggested questions for the workshop to address were requested. Response was excellent and this input was assembled and mailed to all participants approximately one week prior to the meeting. These goals statements and questions presumably reflect individual and company concerns and priorities at the present time. As such, they provide in themselves an interesting current view of heat transfer in relation to turbine engine design.

The goals statements received cover both overall or global goals and specific technical goals. The questions proposed for discussion seem to fall into two categories: those that relate to generic topics such as film cooling and rotational effects, and those that relate to analytical methods or experimental methods in general. Arranged in these broad groupings, the advance input is reproduced in Appendix B essentially unedited. There is, of course, duplication which presumably reflects common concerns among the participants.

Figure 1 attempts to summarize the key words and phrases appearing in both the goals statements and questions in terms of a diagram depicting part of the engine design process. The topics in the upper box are typical of those for which additional heat transfer information is indicated as needed to help achieve design goals. Here for brevity the goal is stated as improved durability. Other alternative goals such as improved SFC could be substituted; but the goals statements indicate that durability is, currently, foremost for much of the industry.

Future additional information on these topics will be generated by both analytical and experimental research. It will ultimately feed through the various design steps including structure analysis and life prediction.

However, uncertainties in both the acquired information and in the life prediction schemes necessarily reduce the utility of the research results in achieving design goals. In setting priorities for future research it seems prudent to consider not only the feasibility of the work but also the degree of real gain to be achieved considering these uncertainties.

With this summary, it was suggested that the workshop participants consider it their task to recommend:

- Problems that need the most attention
- Depths to which they should be explored
- Approaches that show the most promise
- Measures to judge the efforts.

NASA LEWIS PRESENTATIONS

LeRC Organization

(Presented by Robert Simoneau, Heat Transfer Fundamentals Section, Turbine Branch)

Figure 2 depicts a portion of the Lewis Research Center organization related to and as seen by the heat transfer section. The Heat Transfer Fundamentals and Turbine Cooling sections operate within the Science and Technology Directorate, one of the four program directorates at LeRC. The general function of the S & T Directorate is to:

- Plan and conduct R & T programs in the disciplines that have multiprogram applicability.
- Emphasize the long range, innovative and basic aspects of R & T.
- Provide the technological advances that form the foundation upon which the system and experimental programs depend.
- Support the program directorates in our disciplines via the matrix management principle.

Trends in Aeronautical Research R & T

(Presented by Richard A. Rudey, Chief, Aerothermodynamics and Fuels Division)

As we look into the future for the next twenty to thirty years, I believe that there are a number of factors that will be affecting the research and technology that we do in aeropropulsion. These factors will act as drivers or forces that will set the direction of the research and technology that is conducted by both industry, the government and the university communities. These factors break down into four groups: (1) energy conservation pressures, (2) economical pressures, (3) environmental pressures, and (4) political/social pressures. In energy conservation, research and technology efforts will be directed towards supporting new engine designs such as the engines in the NASA E^3 Program. In these designs, increased pressure ratio and some increase in turbine inlet temperature are being sought. Also, in energy conservation, related research and technology will be directed towards developing advanced turboprop engines of which the gas generator core will strive to have high pressure and high temperature capabilities beyond current engine levels. It is difficult to specifically quantify the desirable levels of increased pressure ratio and temperature that will be sought inthe future, but it would certainly appear that pressure ratios in excess of 35:1 are not unreasonable to strive for. In the economics area there are two types of forces that will be guiding the research and technology: (1) development cost and (2) operating costs. Because of the large investment that is needed to develop an all new engine, many of the manufacturers will be relying heavily on producing derivative engines based on currently developed or slightly modified core engine technology. Operating cost increases that are invisioned in the future will be tied principally to engine durability and maintainability and fuel price. From a research and technology viewpoint, particularly the research and technology that is the subject of this workshop, this implies that advancements will be needed in turbine cooling, combustion liner cooling and in the development of advanced materials and coatings. In the environmental area, the principle focus will be on the control of emissions and noise. In the political and social pressure area, the prime focus will be on the declining availability of the strategic materials and petroleum derived fuels. This declining availability will be an important factor in our planned use of the sophisticated alloys which require some of the materials which fall into the strategic material category and on type of fuels that future aircraft must be able to use. Certainly the use of future fuels that are derived from available petroleum, shale oil, and coal, as well as the possibility of using cryogenics and even alcohol, must be considered in our future research and technology efforts. When one considers the above influence, I think the result will be for continued emphasis on high pressure ratio and high temperature cycles for gas turbine engines. There will be an emphasis on the use of alternatives to some of our current approaches, particularly in the area of materials and fuels, and there will be certainly an increase in emphasis on what we might term the "ilities"; that is, durability, maintainability, and so forth. From the viewpoint of today's workshop, the fundamental knowledge of the heat transfer phenomena in the engine hot section will be the key to improvements of durability and maintainability.

The above considerations establish what I see to be the research trends for the next twenty to thirty years. First, I believe there needs to be an increase in our ability to understand and describe the phenomena that are occurring in gas turbine engines. This will require an accurate definition of the environment by making accurate measurements of the phenomena that are occurring in specially designed experiments. Correspondingly, an increased emphasis on computational techniques and the type of experiments that will be needed to verify the accuracy and capability of newly developed computational techniques will also be required. Coincident with this approach will be a deemphasis on large scale type of experimentation. We no longer will be able to follow the old "build-em and bust-em" approach of the past. The cost of this approach is just too excessive to consider in the future. We will also be reemphasizing basic and fundamental types of experiments needed to understand the physics that are involved in both the aerodynamics and the thermodynamics of future engine cycles. And I believe that we will see a reemphasis on developing and maintaining "centers-of-excellence" in engineering and scientific disciplines. This will occur in terms of total resources of both people and experimental and analytical apparatus. At the Lewis Research Center we intend to increase both our experimental and computational capabilities with the intent to create a "center-of-excellence" in heat transfer fundamentals.

A successful response to the above research trends will require the involvement of all sectors of our technical community including the government, the universities, and the industry. The government's role, as I view it, will be to select and investigate critical areas for fundamental generic research, develop the advocacy for research in these areas and to develop "centers-of-excellence" in terms of people and both experimental and computational laboratory apparatus. The university's role will be one of providing support in fundamental research both at university laboratories and at on-site government laboratories. The industry's role will be principally one of conducting selected research to verify the application of certain analytical and experimental techniques, to conduct "proof-of-concept" experiments, to perform system analyses and to conduct large scale experimental and systems technology types of programs. It will also be important that all the sectors of the technical community participate in workshops, such as the one we are involved in today, wherein we can together discuss and determine the most critical research and technology needs. These workshops will help us to identify areas of research having the most leverage for improving our abilities to meet the future challenges and pressures that I mentioned previously and develop the scope and priorities for our research and technology and will serve as a forum for critiqueing the progress that is being made in all sectors of our technical community.

The results of today's workshop will be used by Lewis Research Center staff in the planning process for constructing a responsive heat transfer research program in fundamentals. I consider this workshop to be very important in this process and I hope that your participation will be a fruitful experience for you as well. I certainly thank you for your valuable participation.

Basic Analyses

(Presented by Robert Siegel, Viscous Methods Section, Computational Fluid Mechanics Branch)

Several recent and ongoing projects are described of a generally fundamental analytical nature. Some of the work is being done inhouse at LeRC, and the rest is in conjunction with outside grants or contracts.

Combustion

A fundamental analysis of turbulent flow with combustion is being made by using a numerical "random vortex method." (Univ. of California, Berkeley, grant). In this algorithm the essential features of the flow field governed by the Navier-Stokes equations are simulated by the action of vortex elements that model the turbulent eddies. The random walks of the eddies express the effects of diffusion. The tangential velocity boundary condition at the walls is satisfied by creation of vorticity in the proper amount. The method keeps account of the position and strength of the vortex elements constituting the flow field and is thus gridless. The basic algorithm, augmented to accomodate the effects of flames, has been applied to the analysis of turbulent flow with combustion that is stabilized in the recirculation zone behind a step, as shown in Figure 3.

Significant advances have been made in combustion modeling over the past several years. The use of numerical methods combined with chemical kinetics has given the combustion engineer some ability to predict combustor flow field characteristics. These advanced tools, while still in their early stages of development offer the potential of reducing the design and development time for gas turbine combustors. Because soot has a large radiating ability, the local production and decay of soot must be included, since the radiation depends on soot concentration. The Mie Theory is currently being looked at to help predict soot properties. This information will be incorporated into a more detailed soot radiation model for use in the general numerical modeling procedure.

Interaction of Flow and Surfaces with Turbulence

The external heat transfer coefficients around blades are influenced by the free stream turbulence. This turbulence is known to have important effects on boundary-layer separation and transition. In one study, the effect of flow contraction is analyzed. This shows how large-scale turbulence is modified by a large flow contraction. The turbulent eddies are elongated in the streamwise direction while their transverse velocities are amplified. The second analysis deals with how entropy fluctuations, produced by the combustor, interact with a non-uniform downstream flow. The result is a turbulence production that can be significant in influencing separation and transition.

A flow visualization study combined with analysis is being done on a grant (Colorado State University) to study turbulence in the stagnation region of flow around a cylinder. The studies have revealed the selective stretching of cross-vortex tubes, their streamwise tilting, the emergence of an organized turbulent flow pattern near the stagnation zone, and the interaction of the amplified vorticity with the laminar boundary layer.

Corner and Endwall Flows

The separation region in a two dimensional corner is being analyzed by modeling the region as one of constant vorticity. This leads to a solution of Poisson's equation in the separated region that is matched to a solution of Laplace's equation in the outer flow. The dividing free streamline must be found such that static pressure is balanced across it, and fluid velocities are tangent to it. The analysis is intended to provide insight into the conditions associated with separation. The problem is illustrated in Figure 4.

A basic numerical study is being made (contract with Scientific Research Associates) of three-dimensional laminar and turbulent flow in significantly curved ducts of rectangular cross section. Solutions for both laminar and turbulent flows compare well with available analytical and experimental results. The analysis is based on approximate governing equations that correct an inviscid solution for viscous effects, secondary flows, total pressure distortion and heat transfer. The method appears promising for making detailed predictions of viscous primary and secondary flows.

External Heat Transfer Coefficient

An approximate integral method solution was devised for calculating laminar, transitional, and turbulent convective heat transfer coefficients over the surfaces of turbine vanes. Transition criteria were based on momentum thickness Reynolds numbers in the integral solution. Generally good agreement was obtained with results from a finite difference solution (STAN 5-A), as shown in Figure 5.

An analysis was made to examine the extent to which various factors influence the accuracy of analytically predicting turbine-blade metal temperatures. The factors considered were the gas and coolant temperatures, gas-to-blade and blade-to-coolant heat-transfer coefficients, and wall conductances. Results indicate that the greatest improvement in blade metal temperature prediction would result from improving the accuracy of the local gas-to-blade heat transfer coefficients.

Cooling Processes

A two-dimensional integral method was formulated to predict the local centerline adiabatic wall temperature and the coolant coverage area downstream of a 30° inclined coolant injection hole. Assumptions were made about the coolant layer cross-sectional shape, and the entrainment mechanism involved in mixing the coolant with the free stream. The integral conservation equations were formulated and then solved numerically. Sample results are shown in Figure 6.

The heat transfer characteristics were analyzed for a cooled porous medium having a curved boundary. A general analytical procedure for solving the energy equation was used, combined with a numerical conformal mapping method for transforming the porous region into an upper half plane. Specific results were carried out for a cosine shaped boundary exposed to uniform external heating. Results, illustrated in Figure 7, show the effect of coolant starvation in the thick regions of the medium, and the extent that internal heat conduction causes the surface exposed to the heat load to have a more uniform temperature.

The aerodynamic interaction of heat and mass transfer with steady transonic flow in turbine blade passages is being studied on a grant (Univ. of Tennessee Space Institute). The program is both experimental and analytical. The main objective is to determine if film cooling mass addition and/or wall cooling produces significant alterations in the location of the sonic line and in the strength and losses of the shock system. The one-dimensional compressible flow equations contain terms with $(1-M^2)^{-1}$, and hence indicate that significant effects may occur when M is near one.

Ceramic thermal barrier coatings on hot engine parts have potential to reduce metal temperatures, coolant requirements, cost, and complexity of the cooling system. For heat transfer analysis the radiative behavior of the coating is needed. This is complicated by the fact that the ceramic material is porous and translucent. Calculation of the radiant heat transfer within the nonisothermal, translucent ceramic coating material shows that, with little loss of accuracy, the gas-side ceramic coating surface temperature can be used in the heat transfer analysis of radiation loads on the coating system.

References

1. A.F. Ghoniem, A.J. Chorin and A.K. Oppenheim, "Numerical Modeling of Turbulent Combustion in Premixed Gases," work under NASA Grant NSG-3227.
2. M.E. Goldstein and P.A. Durbin, "The Effect of Finite Turbulence Spatial Scale on the Amplification of Turbulence by a Contracting Stream," J. Fluid Mech., Vol. 98, part 3, pp. 473-508.
3. M.E. Goldstein, "Turbulence Generated by the Interaction of Entropy Fluctuations with Non-uniform Mean Flows," J. Fluid Mech., vol. 93, part 2, pp. 209-224, 1979.

4. W.Z. Sadeh and H.J. Brauer, "A Visual Investigation of Turbulence in Stagnation Flow about a Circular Cylinder," J. Fluid Mech., vol. 99, part 1, pp. 53-64, 1980.
5. J.P. Kreskovsky, W.R. Briley and H. McDonald, "Prediction of Laminar and Turbulent Primary and Secondary Flows in Strongly Curved Ducts," Rept. R80-900007-12 under contract NAS3-22014, Sept. 1980.
6. D.J. Gauntner and J. Sucec, "Method for Calculating Convective Heat Transfer Coefficients Over Turbine Vane Surfaces," NASA TP 1134, 1978.
7. F.S. Stepka, "Analysis of Uncertainties in Turbine Metal Temperature Predictions," NASA TP 1593, 1980.
8. C.R. Wang, S.S. Papell and R.W. Graham, "Analysis for Predicting Adiabatic Wall Temperatures with Single Hole Coolant Injection into a Lowspeed Crossflow," to be published.
9. R. Siegel and A. Snyder, "Heat Transfer in Cooled Porous Region with Curved Boundary," to be published.
10. C.H. Liebert, "Emittance and Absorptance of NASA Ceramic Thermal Barrier Coating System," NASA TP 1190, 1978.
11. H.J. Gladden and C.H. Liebert, "Effects of a Ceramic Coating on Metal Temperatures of an Air-Cooled Turbine Vane," NASA TP 1598, 1980.

Computational Analysis

(Presented by Raymond Gaugler, Heat Transfer Fundamentals Section, Turbine Branch)

First, a distinction must be made between basic analysis and computational analysis in the context of this workshop. Figure 8 schematically represents some of the flow phenomena that influence turbine heat transfer. A basic analysis would be the modeling of any one of these phenomena. A computational analysis is one that combines a number of the basic analyses. This is what is emphasized in this presentation.

A number of programs are currently available at LeRC that could be considered as computational analyses under this definition. The following list of these programs are those considered to be computationally mature, in that a user manual of some sort exists for each:

Boundary Layer Analyses, 2-D

- STAN5, finite difference
- BLAYER, integral

Inviscid Passage Flows

- TSONIC, 2-D, blade-to-blade
- MERIDL, 2-D, hub-to-shroud
- MIT, 3-D, (Thompkins)

Viscous Passage Flow, 3-D

- NANCY (Dodge)

Blade Thermal Analysis, Quasi 3-D

- TACT 1, impingement insert
- FCFC, full coverage film cooled

Structural Analysis

- MARC
- NASTRAN

The fact that these programs exist in a mature format does not necessarily mean that the physics of any problem is modeled perfectly. There is continued effort being expended to improve the above programs. In addition, the following programs are currently under development.

Parabolic Marching, 3-D

- McDonald, turning passage, single pass
- Katsanis and McFarland, iterated marching

Elliptic Navier Stokes

- Steger, 2-D
- Chima and Donovan, 3-D

Blade Thermal Analysis

- TACT 2, Multipass forced convection

The question being addressed in the workshop is what direction should computational analysis be heading in the future? Of course, an ultimate goal would be a numerical solution of the full Navier-Stokes equations, coupled with blade thermal and structural analyses, but perhaps this is too ambitious a goal to seriously discuss at this time. A more realistic approach might be to consider some type of 3-D passage flow analysis, including viscous effects, to which empirical models of some of the basic flow phenomena could be attached.

References

1. M.E. Crawford and W.M. Kays, "STAN5--A Program for Numerical Computation of Two-Dimensional Internal and External Boundary Layer Flows," NASA CR-2742, December 1976.
2. W.D. McNally, "FORTRAN Program for Calculating Compressible Laminar and Turbulent Boundary Layers in Arbitrary Pressure Gradients," NASA TN D-5681, May 1970.
3. T. Katsanis, "FORTRAN Program for Calculating Transonic Velocities on a Blade-to-Blade Stream Surface of a Turbomachine," NASA TN D-5427, September 1969.
4. T. Katsanis and W.D. McNally, "Revised FORTRAN Program for Claculating Velocities and Streamlines on the Hub-Shroud Midchannel Stream Surface of an Axial, Radial, or Mixed-Flow Turbomachine or Annular Duct," I--User's Manual, NASA TN D-8430, March 1977; II--Programmer's Manual, NASA TN D-8431, July 1977.
5. P.R. Dodge, "3-D Heat Transfer Analysis Program," AFAPL-TR-77-64, October 1977.
6. R.E. Gaugler, "TACT1, A Computer Program for the Transient Thermal Analysis of a Cooled Turbine Blade or Vane Equipped with a Coolant Insert," I--User's Manual, NASA TP-1271, August 1978; II--Programmer's Manual, NASA TP-1391, January 1979.
7. P.L. Meitner, "FORTRAN Program for Calculating Coolant Flow and Metal Temperatures of a Full-Coverage-Film-Cooled Vane or Blade," NASA TP-1259, AVRADCOM TR 78-19 (PL), July 1978.
8. "MARC General Purpose Finite Element Analysis Program, User's Manual," Marc Analysis Research Corporation, 1979.

Basic Experiments

(Presented by G. James VanFossen, Heat Transfer Fundamentals Section, Turbine Branch)

The term basic experiments is used here to imply experiments conducted to try and discover underlying mechanisms in areas of heat transfer that are specifically related to the gas turbine. This usually implies that the experiments are relatively simple in comparison to complex turbine rigs. Tests are usually conducted at scaled conditions of flow and temperature in wind tunnels, such as shown in Figure 9. Several of these basic experiments that have been completed recently or are planned for the near future are discussed below.

Leading Edge Film Injection Visualization

A flow visualization study of film cooling near the simulated leading edge of a turbine blade has been conducted. A cylinder was used to simulate the flow around the leading edge, as shown in Figure 10. Smoke was mixed with the simulated cooling air and injected through a row of radially angled holes at various distances from the stagnation point. It was determined that the injected film layer is always substantially thicker than the calculated boundary layer thickness. The film layer was observed to separate from the surface at lower blowing rates as distance from the stagnation point increased. Figure 11 is a typical smoke trace.

Horseshoe Vortex Visualization

Helium filled soap bubbles and smoke were used to investigate the horseshoe vortex formed near the leading edge of a vane in a linear cascade of large airfoils. Fluid from the endwall boundary layer stagnates at the leading edge of the vanes and rolls up in a tight vortex core. The soap bubbles were introduced into the endwall boundary layer and then entrained in the vortex. On the suction side of the vane, the vortex was seen to remain very close to the vane-endwall corner. On the pressure side the vortex moves away from the vane surface and ends up about in mid-passage at the trailing edge, as shown in Figure 12. Methods to control the horseshoe vortex are currently being investigated. Injection of air from a single hole in the endwall directed toward the vane stagnation point was seen to cause the pressure surface vortex to remain close to the vane surface. The controlled and uncontrolled cases are compared in Figure 13.

Thermal Visualization With Liquid Cyrstals

A study is being conducted to evaluate commercially available plastic sheets coated with liquid crystals in combination with various types of film heaters for the purpose of thermal visualization, as shown in Figure 14. Using this technique, isotherms on the surface of interest can be mapped and heat transfer coefficient distributions can then be obtained. Examples of thermal visualization given are the isotherm pattern on a flat plate cooled by a staggered array of impinging jets and the isotherms on the endwall of a linear cascade. The latter is shown in Figure 15.

Coolant Supply Tube Curvature Effect On Film Cooling

A study of single hole film cooling on a flat plate was conducted to determine the effect of coolant supply tube curvature, as shown in Figure 16, on effectiveness. It was found that under certain conditions the film cooling effectiveness was greater with the curved tube, as shown in Figure 17. Studies are continuing to determine the effect of supply tube radius of curvature on effectiveness.

Heat Transfer In Arrays of Short Pin Fins

Heat transfer coefficients have been measured for several pin fin geometries that are typical of those used in the trailing edge of some cooled turbine blades, such as shown in Figure 18. The geometries tested had pins that were shorter (smaller length to diameter ratio) than those available in the literature. Results shown in Figure 19 indicate that heat transfer coefficients for short pins are lower than for the data available in the literature.

Heat Transfer With Coherent Turbulence

Experiments on the effect of "coherent" turbulence on the heat transfer to a leading edge simulated by a circular cylinder, such as shown in Figure 20, are planned. Coherent turbulence is defined as a flow field which contains eddies of a single dominant wave number with their axes all parallel. The intent will be to test the vortex stretching hypothesis and to determine if there is a relation between eddy size and heat transfer amplification factor.

Blade Wake Effects on Heat Transfer

An experimental program is under way to determine the effect of blade wakes on heat transfer to the leading edges of stationary vanes. A rig has been designed to measure average local heat transfer on an annular cascade of simulated vane leading edges, as illustrated in Figure 21. The cascade is to be placed in the wake of a rotor which can generate wake frequencies up to 3 kHz.

Large Low Speed Turbine Facility

Closely related to basic experiments are experiments designed specifically for verification of computational fluid mechanics predictions. A large scale, low speed turbine facility for tests of this nature is planned for future installation at LeRC as shown in Figure 22. This facility will require a 1.5 meter diameter turbine operating at tip speeds up to 60 meters/sec and mass flow rates of 50 kg/sec at inlet temperatures up to 800 K and will require a gear box and dynamometer capable of absorbing 1000 horsepower. The facility will have to be instrumented with the most up-to-date instrumentation such as a Laser-Doppler-Velocimetry, hot wire anemometry, dynamic pressure sensors, infrared optical scanning and a rotating data telemetry system.

References

1. Louis M. Russell, "Flow Visualization of Discrete Hole Film Cooling with Spanwise Injection Over a Cylinder," NASA TP-1491, 1979.
2. Raymond E. Gaugler, Louis M. Russell, "Streakline Flow Visualization of a Horseshoe Vortex in a Large Scale, Two-Dimensional Turbine Stator Cascade," NASA TM-79274, 1980.
3. Steven A. Hippensteele, Louis M. Russell, Francis S. Stepka, "Evaluation of a Method for Heat Transfer Measurements and Thermal Visualization Using a Composite of a Heater Element and Liquid Crystals," to be presented at the 1981 ASME Gas Turbine Conference, Houston.
4. S. Stephen Papell, Robert W. Graham, Richard P. Cageao, "Influence of Coolant Tube Curvature on Film Cooling Effectiveness as Detected by Infrared Imagery," NASA TP-1545, 1979.
5. G. James VanFossen, "Heat Transfer Coefficients for Staggered Arrays of Short Pin Fins," paper to be presented at 1981 ASME Gas Turbine Conference, Houston.

Near Engine Environent Experiments

(Presented by Frederick Yeh, Turbine Cooling Section, Turbine Branch)

There are four large experimental facilities available (or will be available) for turbine cooling studies at LeRC. These are the J-75 Cascade/Flat Plate Tunnel, the One Vane Tunnel, the Warm Core Turbine, and the High Pressure Facility (HPF).

J-75 Cascade/Flat Plate Tunnel

This tunnel is shown schematically in Figure 23 along with a schematic of the four vane cascade test section, Figure 24. It was originally designed as the four vane cascade. Later, a "flat plate" test section, such as shown in Figure 25, was added. The facility is capable of 1255K (1800F) and 8.5 atmosphere operation. Although this is an older facility, it is still very active. Current and planned activities for this facility are:

- Film coolant discharge coefficient with cross-flow

  Objectives are to evaluate and correlate the flow discharge coefficient of film cooling holes with the effect of mainstream crossflow included. Various parameters, such as coolant injection angle, blowing rate, Mach number of mainstream flow, Reynolds number, and gas to coolant temperature ratio, will be investigated.

- Heat flux gage development

  A continuous effort, to develop a heat flux gage suitable for airfoil at high temperatures.

- Advanced cooling concepts

  Porous metals, coated with thermal barrier coatings are being developed.

- Impingement cooling

  Objectives are to evaluate the effects of spanwise thermal gradients and gas to coolant temperature ratios for inline and staggered arrays of impingement jets with crossflow.

- Curved-tube film coolant injection

  Objectives are to evaluate and extend preliminary results obtained in flow visualization studies, using higher Reynolds and Mach numbers and appropriate gas to coolant temperature ratios.

One Vane Tunnel

This tunnel shown in Figure 26 (modification pending) is capable of operating at 2140K (3400F) at 23.8 atmospheres. It was originally designed as a screening rig to screen various airfoil designs for the High Pressure Turbine (HPT). When modifications are completed the plans for this facility will be expanded to include the following topics and objectives.

- Heat flux gage development

  To extend the heat flux gages developed under the J-75 Cascade Flat/Plate to higher temperatures and pressures

- Infra-red data system development

  To evaluate I-R data system operation at high pressures

- Gas-side heat transfer coefficient

  To obtain local heat transfer coefficient distribution and compare with analysis

- Thermal scaling

  To verify thermal scaling laws to higher pressures

- Transition studies

  To investigate transition point, and extent, at various inlet conditions

Warm Core Turbine Facility

This is a turbine aerodynamics research facility, capable of operating at 750K (900F) and three atmospheres. (See Figure 27) It is currently being used for a heat transfer test, where heat transfer coefficients to the turbine shroud will be measured, as shown in Figure 28. This is a well-equipped facility, available for heat transfer studies, but only on a non-interference basis with aerodynamic research.

High Pressure Facility (HPF)

The High Pressure Facility (HPF) shown in Figures 29-31 is the major facility for rotating tests. This is a new facility, currently undergoing final check-out before actual tests can begin. It is designed for 2480K (4000F) and 40 atmospheres. Current plans call for using the High Pressure Turbine in two different modes of operation. The "Low Pressure" mode, and the "Full Scale" mode.

The "Low Pressure" mode will be operated at 530K (500°F) and 10 atmospheres. It was decided to conduct fundamental research at these reduced conditions because it affords better control of experimental variables, and is less expensive to run. The reduced conditions represent scaled conditions of a typical advance turbojet engine. Current planned objectives for the "Low Pressure" mode operation are:

- Obtain heat flux measurements on blades and vanes
- Obtain metal temperature distribution and cooling effectiveness on blades and vanes
- Obtain laser anemometer measurements of mainstream conditions that would affect gas side heat transfer
- Thermal scaling

In the "Full-Scale" mode, the HPT is operated at near real engine environment. It is the final test of the previous development efforts. The planned objectives of the "Full Scale" mode are:

- To verify analytical predictive techniques under near engine environemnts, to point out deficiencies where they occur, and suggest areas where additional work may be required.
- To provide benchmark data in near engine environments (e.g., gas path temperature and pressure profiles, turbulence levels, and heat flux distribution on airfoil). These data will, in turn, be used to improve the analytical predictive methods.

References

1. Gladden, Herbert J., Gauntner, Daniel J., and Livingood, John N.B., "Analysis of Heat Transfer Tests of an Impingement- Convection- and Film-Cooled Vane in a Cascade," NASA TMX 2376, 1971.
2. Meitner, Peter L., and Hippensteele, Steven A., "Experimental Flow Coefficients of a Full Coverage Film-Cooled Vane Chamber," NASA Technical Paper 1036, 1977.
3. Whitney, W.J., Stabe, R.G., and Moffit, T.P., "Description of the Warm Core Turbine Facility and the Warm Annular Cascade Facility Recently Installed at NASA Lewis Research Center," NASA Technical Memorandum 81562.
4. Cochran, R.P., Norris, James W., and Jones, Robert E., "A High Pressure, High Temperature Combustor and Turbine-Cooling Test Facility," NASA TMX-73445, 1976.

Summary of Fundamental Fluid Mechanics and Heat Transfer Programs

(Presented by Robert Graham, Head, Heat Transfer Fundamental Section, Turbine Branch)

The following Table 1 is presented as a summary of the programs in fundamental fluid mechanics and heat transfer that are included in the various categories of LeRC work that have been previously described. It is intended to give a concise overview of both in-house and external work in terms of topic and expected outcome.

TABLE 1

SUMMARY OF PROGRAMS

Topic	Expected Outcome
Pin fin heat transfer	Experimentally determined heat transfer correlation for pin and wall surfaces
Leading edge heat transfer	(1) Comprehensive model of the vortex structure at leading edge. Improved understanding of influence of upstream vortex disturbances
	(2) Develop an improved correlation or analytical approach to predict local heat transfer
	(3) Thermal scaling effects
Unsteady flow heat transfer	(1) A quantitative description of fluctuation in heat transfer in stagnation region imposed by (A) a passing wake (B) fluctuating velocity vector (angle and magnitude)
	(2) Develop and verify an analytical description of unsteady convective heat transfer
Endwall heat transfer	(1) Model of horseshoe vortex and methods of control
Endwall contouring	(1) Application of wall contouring to optimize stator performance
	(2) Assessment of 2D and quasi 3D code for turbine channel design
Film cooling	(1) Modification to existing boundary layer codes to account for wall curvature

TABLE 1

SUMMARY OF PROGRAMS
(Continued)

Film cooling (Cont.)	(2) Assessment of influence of coolant turbulence control on film cooling effectiveness and analytical model explanation
Impingement cooling	(1) Optimum arrangement of impingement cooling
Overall thermal prediction code for turbine blades (TACT)	(1) Prediction of turbine blade temperature incorporating various cooling schemes
	(2) Inclusion of leading edge, unsteady, film cooling, pin pin and impingement advance

New Starts

Topic	Desired Outcome
Transition on turbine blades	Improved transition criteria for application to turbomachinery
Effect of rotation and centrifugal forces on heat transfer and fluid mechanics models	From experiments, a quantitative evaluation of rotational effects on heat transfer models developed in stationary channels
Heat transfer of synthetic fuels employed in regenerative cooling	Heat transfer coefficients for system heat exchangers

HOST (Hot Section Technology) Program

(Presented by Daniel Gauntner, Manager, Hot Section Technology Program)

The Turbine Engine Hot Section Technology (HOST) Project is NASA's new cooperative effort with the U.S. aircraft engine industry. This five to eight year effort is directed at improving the analytical and predictive tools that are needed to increase the "designed-in" durability in the hot section components of advanced aircraft turbine engines. The combustor and turbine sections, while having twenty percent of the engine's weight, account for sixty percent of the maintenance costs. In addition, increasing costs for jet fuels and sophisticated engine development test systems make an improved analytical design more important. The HOST project will generate improved predictive tools that will better describe the complex thermal-mechanical environment and loading conditions within the hot section.

These improvements can be achieved only with vigorous technology development efforts, beginning with hot section benchmark testing to obtain data for evaluation of current analytical and predictive tools. Parallel and follow-on efforts will be conducted to develop the technology for these improved tools in the areas of combustor and turbine environment, component specific modeling, high temperature instrumentation, material constitutive behavior, structural analysis, and life prediction. The component modeling will be focused primarily on the combustor liners and the turbine blades and vanes. The results of these initial and follow-on efforts will be combined and incorporated into the predictive tools and disseminated throughout the U.S. aircraft engine industry.

The activities within HOST will be conducted in coordination with the NASA R & T base efforts. A modest share of the project's activities will be accomplished in-house at the Lewis Research Center. Most of the efforts will be awarded to U.S. research institutions and U.S. aircraft engine manufacturers. Following successful demonstration of the improved analytical and predictive systems technologies, the U.S. engine companies will be in a position to proceed with confidence toward development of new and more durable commercial engines for the 1990's and beyond.

The overall HOST program areas are summarized in Table 2. The planned Phase I activities are in Table 3. Those phase I activities specifically related to turbine heat transfer are further detailed in Table 3.

TABLE 2

HOST PROGRAM AREAS

- Thermal Mechanical Loadings
- Material Behavior
- Structural Analysis
- Accurate Life Predictions

TABLE 3

ACTIVITIES -- PHASE I

- Combustor Performance Modeling
- Vane and Blade Thermal Loading
- Instrumentation Development
- Materials Cyclic Constitutive Behavior
- Structural Analysis
- Life Prediction

TABLE 4

VANE AND BLADE THERMAL LOADING ACTIVITIES

1. Gas Path Analysis
    - 3D Channel Flow
    - 3D Rotating Airfoil
    - Real Environment Tests

2. Gas Side Heat Transfer
    - 2D Heat Transfer - Cascade
    - 3D Heat Transfer - Non Rotating
    - 3D Heat Transfer - Rotating

3. Coolant Side Heat Transfer
    - Impingement Cooling
    - Augmented Convection
    - Entrance/Rotation Effects

4. Metal Temperature
    - Interface Metal Temperature and Structure Codes
    - Update Gas and Coolant Side Coefficients
    - Test Codes

WORKING GROUP REPORTS

New Engine Environment Experiments

(Editor's note: Two separate working groups were organized to discuss new engine environmental experiments. Their reports were quite similar and have been combined for clarity.)

Participants

Group A	Group B
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Evans	Cochran
Gladden	Epstein
Mahan	Gauntner, J.
Papell	Meyer
Patton	Wesoky
Rohde	Yeh
Stepka	

Recommendations

Engine or near engine environmental work is needed because:

- Temperature scaling is questioned
- Turbulence effects are important
- Rotation effects are important
- Geometry effects are important

Specifically engine or near engine environmental work is needed in the following areas, listed in rough priority order:

- External heat transfer
- Gas temperature distributions
- Rotor/Stator endwall region cooling
- Rotational effects on internal cooling and flow distribution
- Blade tip and tip shroud heat transfer
- Instrumentation development, especially for external heat transfer and gas temperature distributions
- Cavity and rim flow effects
- Combustor liner cooling
- Thermal and aero performance of thermal barrier coatings
- Film cooling
- Radiation heat load on vanes

The latter two topics, film cooling and radiation heat loads, would become relatively more important if TIT were to increase substantially. However, the current consensus is that commercial engine TIT's will not go much higher than 2800F or so.

External heat transfer is listed first in the above list, indicating that it is probably the most pressing current problem area. This area can be further broken down as follows:

- Transition behavior with pressure gradients and curvature (i.e., vane and blade geometry)
- Effects of turbulence
- Effects of roughness
- Effects of rotation and wakes

Most basic experiments to check transitional turbulence models must include pressure gradients and high turbulence level.

Approaches, especially where NASA could contribute, are suggested as follows:

- Instrumentation development for hostile environments, especially heat flux, turbulence, and temperature sensors.

- Full engine testing. This approach is expensive with major difficulties associated with getting instrumentation out.

- High spool engine testing. This approach gives up only pressure level for easier instrumentation. Pressure level is not important except for cyclic endurance testing.

- NASA Vane Cascade and High Pressure Turbine Facility. These facilities provide good engine simulation of temperature level and turbulence. Work should continue on development of high temperature heat flux sensors to make direct heat flux measurements in facilities like these.

Finally, the overall need for coordination between the experimenter and the analyst is emphasized. Experiments must be well designed to give the analyst the right data to check out prediction systems properly; and analysts must develop prediction systems which reflect the needs of the real world. Such coordination is essential for success in improving engine durability.

Basic Experiments

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Simon
Suo
Van Fossen

Recommendations

First, the group defines basic experiments to be those which isolate and investigate an important aspect of a problem area. In addition, they must be well documented and provide the physical understanding required to allow an extrapolation beyond the data set.

As a general prioritization of needs in basic experiments, the consensus is that problems that need most immediate attention are primarily those associated with predicting external heat loads. Second in priority are problems associated with internal cooling.

The following list are those recommended basic experiments (in rough priority order) which satisfy an immediate need for present airfoil heat transfer prediction schemes. These are two dimensional or quasi-two dimensional experiments.

- Transition
- Turbulence/unsteady flows
- Separation/reattachment
- Curvature
- Large acceleration
- Film cooling
- Internal cooling with rotation
- Temperature ratio

A second list is recommended as basic experiments which will help to establish future gas turbine gas path heat transfer prediction schemes. These are three dimensional experiments.

- Intrarow gas temperature re-distribution to determine local driving potential for heat transfer
- Three dimensional turbulent boundary layer heat transfer
- Separation
- Unsteady flows
- Off-design flows

As a general recommendation, the group agrees that experiments must be designed to verify the design system at various levels of sophistication. Inherent in this recommendation is a belief that such verification is essential to achieve confidence in the design system as an accurate predictive tool for new designs.

The general area of basic experiments is one where contributions can be made jointly by NASA, industry, and the universities.

- Wind tunnel experiments are natural for universities
- Rotating, multi-row turbine experiments are natural for industry
- NASA can do either

Finally, some discussion concerned information flow between industry and the universities, and it is recommended that NASA increase its role as an interface between these two groups.

Analysis

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Recommendations

- Establish a clearing house to collect and evaluate available data. After evaluation, needed experiments can be recommended for use in validation of prediction methods.

- Concentrate on development of program modules rather than general codes for design.

- Many questions remain on airfoil external heat transfer. Among these are effects of transition, turbulence, and thermal scaling. The data base is inadequate for the needs of analysts, and needs to be enlarged, particularly a data base for combined effects.

- Three dimensional inviscid analyses are needed which include adequate solutions to the energy equation. This capability is needed for blade rows to define the local driving potential for heat transfer.

- More attention is needed on turbulence modeling. This is the pacing item for prediction of very complex three dimension flows.

- Basic studies are needed on the modeling of Reynolds heat flux terms. The present Reynolds analogy approach is questionable for some flows.

- Work is needed in film cooling, in terms of better organization of existing data and more work on basic analyses. Prediction of film cooling at present is a weak point.

- More work is needed on unsteady flow effects on heat transfer; both additional data and analytical work are needed.

- Analytical methods and data are needed for rotating cavity heat transfer.

- More analytical effort is needed on endwall heat transfer both with and without film cooling.

- More information is needed on the importance of the horseshoe vortex to heat transfer.

SUMMARY

Overview

This section is the editor's attempt to convey both a summary of the working group recommendations, and also impressions of the meeting as a whole. These impressions are based on observations of all the working groups in session, study of the notes and transcripts from the deliberation and reporting sessions, and discussions with many of the participants.

First, the organizers attempted, through the mechanism of the pre-workshop input distributed in advance, to bring the most pressing problem areas into focus early. The desired result was that the workshop groups could devote the primary efforts at Cleveland to deciding which problems were of the highest priority, which methods of attack were the most promising, and which groups were the best suited to the various tasks.

The pre-workshop input did highlight many areas of common concern; but the working groups, once in session, displayed a strong reluctance to be focused on any limited number of problem areas. A wide diversity of opinions and perceptions were aired. All of the groups had great difficulty in prioritizing problem areas. The rough rankings given in the working group reports represent a considerable amount of compromise. Promising methods of attack and allocation of resources were discussed only in general terms.

Part of the working group difficulty in getting down to specifics is certainly a result of the sizes of the groups. Two groups each for analysis and basic experiments and only one group for near engine experiments would have been, in retrospect, a better arrangement.

In reality, however, the difficulties experienced by the groups in formulating specific recommendations are probably just reflective of the underlying complexity of flow and heat transfer in gas turbine engines. We know that there are many phenomena occurring in these engines that are not understood. We have names to describe the phenomena; but all of us are not in agreement even on what the names imply. We are simply not sure what effects or questions are the most important in terms of improving our design systems. We do agree that fundamental work is needed to build our understanding of the phenomena, especially when they occur in combination.

It may well be that the unexpected overpopulation of the analysis and basic experiments groups, and the lower than expected turnout for the near engine experiments group, reflects recognition on the part of the participants that improved understanding of the basic phenomena is essential; and that this is not likely to be achieved through near engine environment testing. Indeed, the consensus of all the groups appeared to be that testing at very near engine conditions should concentrate on the task of better defining the engine environment.

In comparison with the previous similar meetings in recent years, there was much more discussion emphasis on the overall flow and heat transfer problem in terms of combined effects of the many phenomena that exist in the real engine. There was also much more discussion of numerical computation of the overall problem. These two observations are of course not unrelated. This fast growing capability in computation is one of the major driving forces creating need for a better definition of the engine environment and need for a better understanding of the flow physics.

The traditional basic experiments that study an isolated single effect have obvious shortcomings. First, they are usually conducted under conditions far removed from the actual severe engine environment. Second, they leave open the question of possible important interaction between multiple effects. Third, they often do not document all of the information needed as boundary conditions in a numerical simulation of the experiment.

On the other hand, experiments conducted with more near prototype geometries and conditions have their own set of shortcomings. They are more often than not non-generic, and are conducted with questionable uncertainty levels. They share with the more simple experiments the problem of full documentation of information needed for numerical simulation.

In the working group and reporting sessions, there was clearly not full agreement on what types of work have already been adequately done, on what had already been demonstrated, etc. There was also recognition that in many areas, film cooling for one, large volumes of data from different sources exist, but are in need of a systematic evaluation and summarization. Many participants felt that this situation could be improved through the creation of some sort of clearinghouse or data repository, but this is obviously difficult to do in a way that would be truly useful to designers.

The people most involved in the actual design process also expressed concern about the direct usefulness of the rapidly developing computational capability as a design tool. They pointed out the time that has been traditionally required to incorporate a new technique into a particular design system. The consensus of industry seemed to be that these computational tools would probably be most readily used if they were made available in modules that could be tailored by each company for their particular use. Along these lines the point was made that industry could make good immediate use of modules that stop short of full 3-D viscous solution capability. One example mentioned several times was the need for a good 3-D inviscid code that could predict gas path temperatures downstream of the combustor exit profile.

Another related point with direct bearing on the utilization of new information and techniques in design is the problem of training designers in their use. This problem in turn is related to the alarmingly low present enrollments in engineering graduate schools which was discussed at the meeting.

General Recommendations

The recommendations from the working groups focus on problems associated with heat transfer from the external gas path; they do not focus on cooling techniques per se. This is partly the result of recognition throughout the industry that there are very significant gaps in our knowledge of the gas path heat transfer. The uncertainty in gas path heat loads prevents optimal decisions on the use of cooling air and truly hinders efforts to improve durability and performance.

This focus at the workshop was probably also strongly influenced by the fact that all of the discussions became very much entwined with the developments in numerical computation. These computational developments at present are concentrated on gas path analysis rather than internal cooling flow analysis. As a result, some important problem areas that were mentioned in the pre-workshop input received little attention. For example, the problem of cavity heat transfer and its implications on turbine durability and clearance control was probably discussed far less than deserved.

For the gas path heat transfer and all other problem areas, it appears that there are advocates and sound arguments for a wide range of future experimental work. The goals of this work are both to provide immediate help to the designers and to provide the necessary validation of computational techniques at several levels of flow complexity.

These experiments must span the spectrum from single effect modeling experiments to very near engine environment experiments. More emphasis than in the past must be placed on modeling experiments that treat several effects simultaneously; and more emphasis must be placed on developing near engine experiments that are as generic as possible. The consensus seems to be that experiments that are designed to run at or very close to actual engine conditions should, for the present, have as their principal objective the definition of the engine environment. Along with this, efforts should be increased to develop the instrumentation necessary for environment definition.

Recommendation for NASA

Since one of the main purposes of the workshop effort is to provide NASA with advice concerning its own future work in fundamental heat transfer, it seems appropriate to conclude with a summary of expressed needs that NASA appears to be uniquely in a position to fill.

First is a recommendation that NASA increase its present activities as an interface between industry and the academic community. It should continue to identify and fund work at universities that are compatible with university time scales and resources. In this way it can encourage utilization of the academic community in gas turbine technology and encourage graduate study in areas relevant to the industry. As part of the interface activity is a recommendation that if data repositories and data evaluation functions are to be established, that NASA assume the responsibility for initiating and coordinating such activities.

Second, NASA should continue and probably increase its efforts in the development of instrumentation that can be used to better determine the engine environment under actual operating conditions. A particularly critical need is the ability to measure turbulence in real environments. The actual engine testing should probably be done in industry so that information from a wide spectrum of different current technology engines can be accumulated and summarized.

Third, NASA should continue to develop an intense and ongoing dialogue with industry in regard to its own efforts in both the computational area and in the HOST program. In order to gain maximum usefulness from both these important activities, it is important for NASA personnel to be continually well informed about the character of the design system that the information will feed into.

The fourth, and perhaps most important recommendation concerns NASA's own in-house experimental work. NASA has resources that enable it to do a wide range of testing from very basic through near engine work. However, the best use of these resources appears to be in the realm of basic experiments in cases where conditions are beyond most university capabilities, and in full scale testing with engine geometries. NASA should seek to develop flexible facilities that are capable of interchanging hardware of different manufacturer's designs, so that the overall results are representative of a range of current design practice.

Finally, NASA should endeavor, in all ways possible, to improve communication, coordination, and support for all segments of U.S. gas turbine technology, industry, government, and universities. This effort is important if this technology, operating within our particular government and free enterprise system, is to remain competitive in the face of increasing world competition.

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APPENDIX B: GOALS STATEMENTS AND QUESTIONS SUBMITTED BY PARTICIPANTS PRIOR TO MEETING

Goals Statements

"The overall development goals of our group are currently aimed to meet the needs of:

- Improved SFC,
- Increased component durability, and
- Cost reduction via improved engineering productivity.

Both experimental and analytical Heat Transfer Technology programs in support of the above goals are in progress.

The experimental programs include:

- Film cooling and heat transfer coefficient measurements on turbine airfoils in cascade and air turbine facilities.
- Acquisition of combustor liner film cooling and heat transfer data in wind tunnels and from engine measurements.
- Measurement of heat transfer on rotating surfaces.
- Component heat transfer measurements using model tests.
- Development of improved instrumentation for heat transfer data acquisition."

* * *

"Global Goals:

- Double the life of hot section parts relative to those in first generation high bypass ratio engines.
- Reduce the cost of hot section maintenance by 30%. (The above goals cannot be obtained at the expense of performance. Engine component efficiency requirements will continue to increase.)

Technical Goals:

- Develop improved analytical prediction methods to optimize existing cooling capabilities.
  - -Local gas temperatures.
  - -Gas-side heat transfer.
  - -Internal heat transfer.
  - -Film cooling.
  - -Life prediction from metal temperatures.

- Develop more effective cooling schemes.
- Develop new materials and both metallic and ceramic coatings for increasing airfoil and platform life."

* * *

"One area we will be emphasizing is film-cooling design and manufacturing technology. Our growth engines and numerous preliminary design studies show the need for cooling techniques applicable to turbines in the 2400-2800°F range. Current impingement convection designs are not efficient at these temperature levels so we anticipate much more routine use of film cooling. It seems to me that the industry does not have a systematic design approach to design of film cooled components. There is a need for more complete and better organized data base regarding configuration effects on film cooling and for verified predictive methods. Within the design process there must be optimal decisions made regarding impingement-film cooling pressure drop splits, location of film cooling holes, etc. Intelligent trade-off decisions must be between the performance penalties associated with film-cooling versus the structural life benefits. Advanced manufacturing technologies, such as laser or electro-stream drilling, must be evaluated for their potential in producing better geometries and lowering costs. In short, it seems that there is much work required to establish film cooling as a well developed design technology.

The second major area I see in the future, reaching well past five years, is the need for treating the total problem of turbine cooling and structural life. Closer coupling of these two disciplines is required to develop the ability to make design decisions with validated life models. We see LCF failures as accounting for an increasing percentage of durability problems. An attack on this problem requires a full transient analysis capability with lower uncertainty levels that exist with current heat transfer and structural models."

* * *

"One of the major goals for advanced engine development ... is to complete the design, development and manufacture, and test a 2600°F firing temperature water cooled gas turbine for use in a combined cycle power plant using coal derived fuel."

* * *

"In the power generation field increasing fuel costs are placing a premium on thermal efficiency. Another major requirement is fuels flexibility, which is the ability to burn a wide range of gaseous and liquid fuels. For performance improvement it is expected that gradual increases in turbine inlet temperature and cycle pressure ratio will be planned and achieved. The development of the combined cycle plant, which offers a 43-46% thermal efficiency, will also be emphasized along with the coal utilization. Increased reliability to reduce down-time and maintenance costs will also be emphasized."

* * *

"The overall goals of my group in engine development are to improve turbine temperature capabilities of industrial gas turbines. This is to be done by transferring the state of the art in aircraft engine technology to industrial gas turbines wherever possible and to develop new technology where required."

* * *

"... not involved in "engine development" per se. We are involved with the investigation of fundamental heat transfer phenomena as they pertain to gas turbine problems. We are also involved in investigating several operational gas turbine heat transfer problems ... Let me be a little more specific and list some of the specific projects that are presently in progress:

- Design of eductor system for cooling the exhaust ...
- Study of a waste heat boiler design ...
- Investigation of exhaust gas fouling of waste heat boilers."

* * *

"... the goals of my group are (1) to investigate and to provide guidance on aerodynamic and heat transfer mechanisms occurring in turbine and compressor environments, (2) to provide experimental data on various physical mechanisms for the development of the next generation of turbomachinery analytical tools (especially boundary layer analyses), and (3) to acquire detailed benchmark data on complex geometries for physical modeling and for comparison with the results of advanced analyses (e.g., 3-D viscous and inviscid codes)."

* * *

"Our goals in the area of gas turbine engine development over the next five years as we see them today include:

- Further development of analytical techniques for predicting compressor performance, including stall,
- Development of design strategies for "quiet" engines, including reduction of fan and core noise,

- Further development of on-rotor instrumentation, including LDA,
- Development of technology for reducing turbine blade erosion in the heavy fuel development,
- Further development of analytical techniques for predicting the onset of combustion instability."

* * *

"In answer to your first question on my goals: (1) In a broad view, to gain a better understanding of three-dimensional fluid flows and processes by which they separate. In a narrower view, to understand and model the three-dimensional flow in the endwall region of a cascade of turbine airfoils ... (2) To study important heat transfer problems in gas turbine engines. The areas that I want to concentrate on are those that, based on my experience ... have been neglected. An example of this is component life, or durability. Too often this question of component life has been left in the hands of stress analysis engineers, when the *real* problem (such as compressor or turbine disk low cycle fatigue) is the adverse affects of heat transfer (for which many times something can be done)."

* * *

"The overall goals of the gas turbine program under my direction is to provide engine companies a method of accurately predicting heat loads within the hot gas path turbine passages. Particular problems that are currently being addressed are the effects of turbulence and unsteady-periodic flows on leading edge heat transfer, heat transfer with separation and reattachment, and heat transfer in three-dimensional flows."

* * *

"Our heat transfer group has not been directly involved with engine development as such, but rather, we have been working on the development of improved computational schemes for complex turbulent flows which should ultimately prove useful in the engine design process. This work includes development and evaluation of both the computational approaches and the turbulence modeling."

* * *

"The principal goal in my particular area of responsibility is the development of analytical methodology (and experimental verification of same) directed toward reliable prediction of local gas to wall heat transfer rates to the external surfaces of turbine nozzle guide vanes and rotor blades."

Questions Related to Generic Topics

Life and Durability

"What are the weakest links in existing life prediction methods?"

"Can we effectively increase component life by minimizing the effects of thermal stress cycling by finding ways to keep a component at a near-isothermal condition at any instant during a flight cycle?"

"Most thermal analyses of new gas turbine combustors are based on the assumption of steady flow. How can we identify those aspects of the unsteady flow which contribute to thermal cycle fatigue? What useful dimensionless groups can be identified for predicting failure times? Can design strategies be developed based on unsteady thermal analyses which allow thermal cycle fatigue damage to be minimized?"

"Based on the uncertainties in the analytical prediction of correlation of variables such as h_g, h_i to at best ± 10% a NASA report by Stepka shows that even then we will not be able to predict steady state metal temperatures with certainty better than ± 50°F. This temperature uncertainty can account for order of magnitude in life. Doesn't this indicate that experimentation with the designed hardware will always be necessary to reduce the uncertainty and doesn't this also raise questions about the need or practicality of complex analyses which may not improve the accuracy of the first design?"

Boundary and/or Environmental Conditions

"What features of the engine environment should be modeled; e.g., is it necessary to know gas path turbulence levels and scales? How would these be measured?"

"Should there be more emphasis on the complex gas temperature distribution phenomena through the turbine and in the airfoil passages due to stage energy distribution and secondary flows in our prediction technique's research and development programs?"

"The local gas environment, particularly local gas temperatures, are not well-known, predictable or presently controllable. Since these are directly related to predicting metal temperatures, what plans are underway to improve knowledge and prediction capability in this important variable? What are suggested research to improve the prediction capability for this important variable?"

Film Cooling

"There is a need for better correlations to unify the wide variety of data with its many parameters."

"Do we really understand the basic problem of mixing of two streams of different temperature and different velocity?"

"Film cooling effectiveness. Do we keep to the traditional approach to the concept of film cooling effectiveness, or adopt the approach used by Kays et. al. of Stanford (i.e., the Nusselt number approach)? What about the new transient techniques such as being used at Calspan (Mike Dunn) and at Oxford University?"

"The controversy of isothermal versus adiabatic film cooling effectiveness research has long been lingering. A consensus on the definition of the needs for both may place this question in its proper perspective."

"What is the effect of extreme variable property environments?"

"Where do we stand on the accurate prediction of effects of transpiration and discrete hole cooling on heat transfer under the extreme variable property environments characteristic of actual gas turbine operating conditions? Much of the experimental data which have guided the development of turbulence models for these effects has been taken under nearly constant property conditions. Have these models been adequately evaluated for the much higher temperatures and heat fluxes of actual engines?"

"How do you model a multislot film cooling configuration?"

"What is the future role of transpiration cooling?"

"We know that we must cool and protect some turbine hot section parts by film, transpiration and multihole cooling. What are the ways that we can manage the injection of this cooling air to minimize (and even reduce) main gas path aerodynamic losses?"

"Aerodynamic losses associated with film cooling--how do you analyze them?"

"What is the importance of shock wave interaction with film cooling?"

"Uncertainties regarding the separate influences of distributed surface injection (film cooling) on turbulence generation, near wall temperature dilution, and downstream thickening of the boundary layer."

"What will be the role of film cooling, if future fuel specifications for aircraft engines allow a particle laden hot gas flow?"

Turbulence and Unsteady Flows

"Many recent advances in the analytical or computational treatment of complex turbulent flows have been guided primarily by experiments in which temperatures or heat fluxes have not been measured. Predictions of heat transfer can be made for most of these flows using a form of the Reynolds analogy in the turbulence modeling. Can we identify flow conditions in which this type of extrapolation might be particularly misleading and in which additional thermal measurements are urgently needed to substantiate turbulence modeling for heat transfer parameters?"

"It appears that the total free stream turbulent disturbance as well as its intensity and length and time scales have a large effect on airfoil heat transfer which has not yet been correlated. What is the status of efforts to systematically understand the turbulence effects on airfoils under realistic Mach No., Reynolds No. and wall cooling conditions?"

"Uncertainties regarding the influence of free-stream turbulence on local heat transfer rates in the laminar region as well as on initiation and extent of the transition region."

"Limited understanding of role of airfoil surface curvature on turbulence production/dissipation and boundary layer stability. A corollary concern involves the role of curvature in the generation of Goertler vortices along the concave surface."

"What is the influence of free stream turbulence on laminar heat transfer in the stagnation region?"

"What are the periodic flow effects due to blade passing--especially in the thin boundary layer at the leading edge."

Transition and Separated Regions

"Uncertainties regarding the surface location at which transition is initiated as well as the surface extent of the transition zone."

"Length of transition zone along surface?"

"Location of transition with competing effects present: cooling of boundary layers; pressure gradient; curvature; formulation of transition model?"

"How are separation bubbles initated--pressure gradient required? What determines size? Prediction of heat transfer inside a bubble?"

"What turbulence modeling do we use in conjunction with predicting separation and reattachment?"

Rotational Effects

"Uncertainties regarding the influence of Coriolis and buoyancy forces on thermal/momentum boundary layer development and stability for rotor blade surfaces with and without film cooling."

"How is the effect of rotation being included in the calculation of gas side heat transfer coefficients? Is there any experimental evidence to show such an effect?"

"What are the effects of rotation on external flow, boundary layer stability, film cooling flows, internal blade passage, and inside disk cavities?"

Curvature, 3-D, and Other Complex Effects

"Advances in computational fluid mechanics along with available experimental data permit the prediction of turbine airfoil heat transfer coefficients, including the effects of curvature, pressure gradients and turbulence intensity. However, questions on boundary layer transition, the effects of wakes, rotation and secondary flows still remain unanswered. Is it realistic to anticipate that these effects will be able to be predicted analytically in the foreseeable future?"

"Have the effects of surface curvature and free stream acceleration been adequately separated and understood for airfoil heat transfer?"

"Effects of streamline curvature on wall heat transfer."

"Where do we stand on endwall regions, corner regions, free stream convergence effects, secondary flows?"

Internal Flows

"Should there be additional work directed towards internal heat transfer coefficients (impingement, pins, roughened surfaces, entrance effects, etc.)? If so, in what areas should the emphasis be placed?"

"Passages of irregular cross-section inside blade need study."

Miscellaneous

"How are heat and mass transfer mechanisms interrelated in a catalytic combustor? How does this interrelation affect performance?"

"Any significant heat loads due to thermal radiation?"

"What are the effects of combustor radiation?--with more soot due to alternate fuels?"

"How well do analytical descriptions of heat transfer in the presence of a thermal barrier coating agree with experience? Is the operative mechanism well understood?"

Priorities and Cooperative Arrangements

"Which areas should be worked that would give the quickest/greatest pay-off?"

"With regard to questions, I am always interested in what others in the technical community perceive as important areas of turbine design which are overly dependent on previous experience and rough correlations as opposed to basic analytical models."

"What form of results are most useful, i.e., computer programs, raw data, correlations, etc.?"

"What is the natural divide between research work industry can (and must) perform and that which a university can carry out?"

"What is the best way to transfer information between the engine companies and the university system? Can this method be implemented?"

"To what extent would industry or the academic community be interested in a cooperative research project utilizing any existing NASA facilities--including the new HPT facility. What are some possible combined research programs or in what areas are they possible?"

"To what extent do you believe there should be duplication of facilities by Lewis when such facilities exist in industry? What are the views on Lewis building a large low speed turbine facility when time to get it operational may be four to five years and there are such facilities plus experience already existing in industry?"

Questions Related to Analytical Approaches

"What are the limitations and level of capabilities of current computational techniques?"

"Wake passing frequency, turbulence, curvature, temperature ratio, and secondary flows, to name a few, all contribute to the external heat transfer problem and prediction techniques. Since present test procedures appear prohibitively expensive and complex to handle all of the existing environmental levels of effects and geometry variations, what is the present status and prognosis of validated computer programs that can or will in the future reasonably evaluate these heat transfer effects on a variety of turbine airfoils?"

"How complex can a computer code be before it becomes useless (i.e., is it more economical to build several engines and test them)?"

"With respect to calculations of turbine heat transfer, which approach should have top priority?

- Development of complex 3-D analyses, including high level turbulence models.
- Quasi 3-D analyses with generalized correlations to handle special regimes (i.e., free stream turbulence effects, boundary layer transition, separation, etc.)"

"What are the most urgent needs in the following three categories?

- Numerical prediction schemes
- Turbulence modeling
- Experiments to guide development and verification of prediction methods."

"What are the more promising approaches to be followed in developing a more complete, general, and reliable theory for the prediction of transition on turbine vanes and blades?"

"What are the more promising analytical approaches to be pursued in accounting for the effect of free stream turbulence level on turbine blade transition and heat transfer?"

"Lack of precision
in the prediction of the inviscid flow field around the airfoil, particularly in the forward, highly accelerated stagnation region."

"What is status of analysis of 3-D boundary layer with heat transfer--especially with respect to endwall heat transfer?"

Questions Related to Experimental Approaches

Data Base

"Lack of a systematic data base relative to the influence of airfoil surface roughness on boundary layer turbulence."

"Is there a need for data with variable properties--data on cooled surfaces rather than heated surfaces?"

"In order to properly verify any analytical models for airfoil heat transfer, an appropriate data base of actual turbine measurements is needed. What techniques should be used to get this data, and what is the status to date?"

"What should be the balance between benchmark tests, engine simulation tests and full scale engine tests; i.e., how should developing prediction methods be evaluated?"

Similitude and Scale

"Heat transfer and flow phenomena in rotating cavities are very complex. Presently, heat transfer analyses in engine applications are based on data obtained for the specific configuration. The question of the utility of experimental programs based on generic compressor and turbine rotor configurations deserves consideration as a source of data for verification of computational models and for specific design applications."

"How much confidence can be placed in very large scale experiments where only limited similitude is achieved?"

"Are tests conducted at scaled conditions, (i.e., low T and atmospheric pressure) useful?"

"How far must we go for similitude in experiments? True similitude of all variables is impossible, short of an actual engine test. How much similitude is required before extrapolation of the data to engine conditions is reasonable?"

"What can be done in regard to measuring the actual engine conditions?"

"What is being done to determine the engine conditions such as turbine turbulence level, scale, etc.?"

Techniques and Instrumentation

"To what extent do researchers feel comfortable conducting heat transfer tests with heat flow out of surfaces when actual heat flow is inward and with small T when actual is large?"

"Recent publications and work indicate increased interest in shock tunnels and isothermal light piston tunnels facilities in order to measure and evaluate airfoil surface heat transfer and film effectiveness distributions. Could this be considered as a cheaper and more viable approach to future test programs over conventional steady state cascade testing?"

"How can we translate cascade results to rotational components?"

"Since verification of any prediction method requires use of a near-engine environment, what instruments are operationally available and to what extent should instruments be developed to obtain the necessary measurements (e.g., accurate measurement of metal temperatures, gas side local temperatures, pressure, heat flux, turbulence, and turbulent structure)?"

"What is the status of efforts to define the turbulence characteristics at the entrance to successive turbine balde rows? What instrumentation is required/preferred?"

"What is the feasibility of liquid crystal thermography to visualize surface characteristics of flows?"

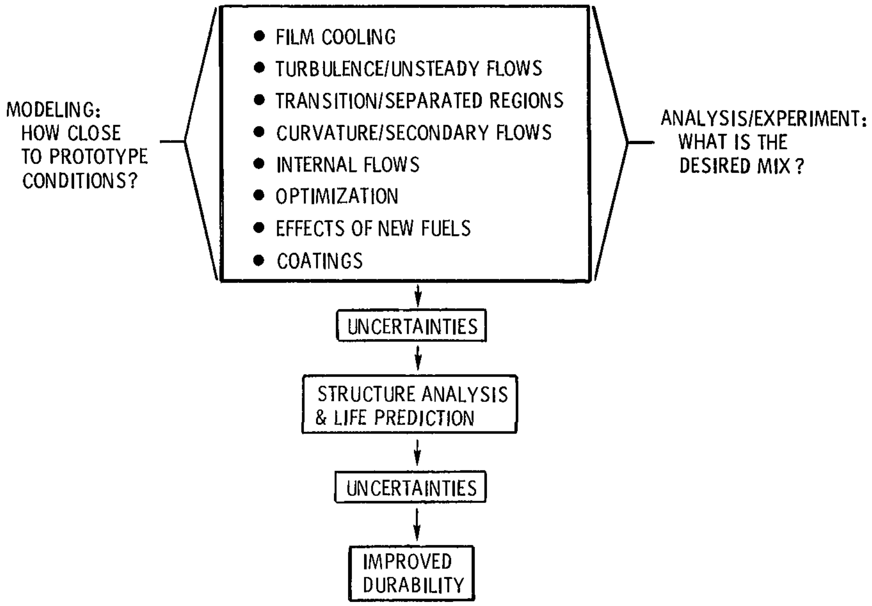


Figure 1. - Summary of key words highlighting pre-workshop input.

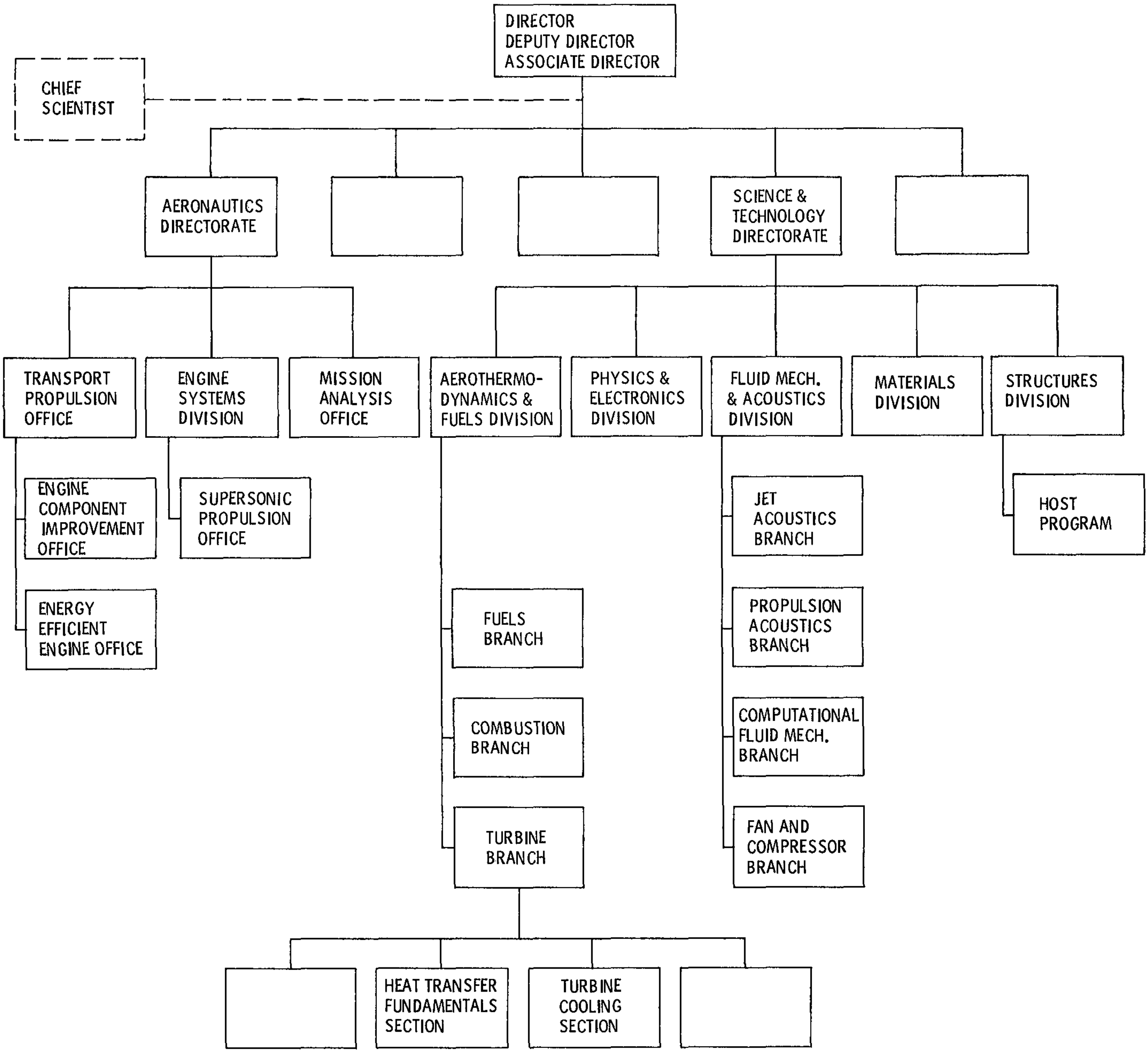


Figure 2. - The organization chart (as seen from the heat transfer sections).

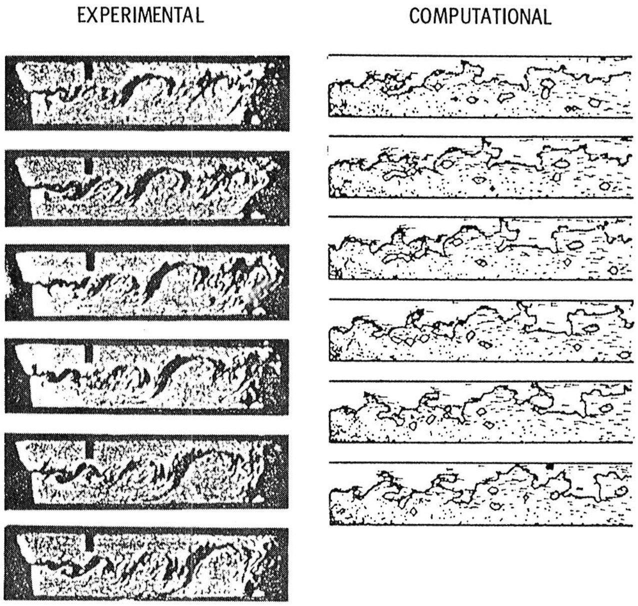


Figure 3. - Combustion at back-facing step.

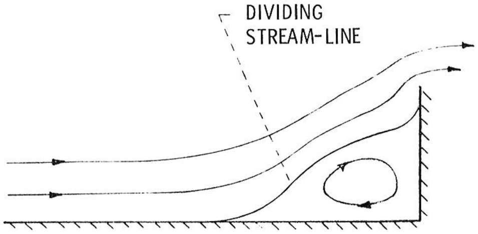


Figure 4. - Separation in a corner.

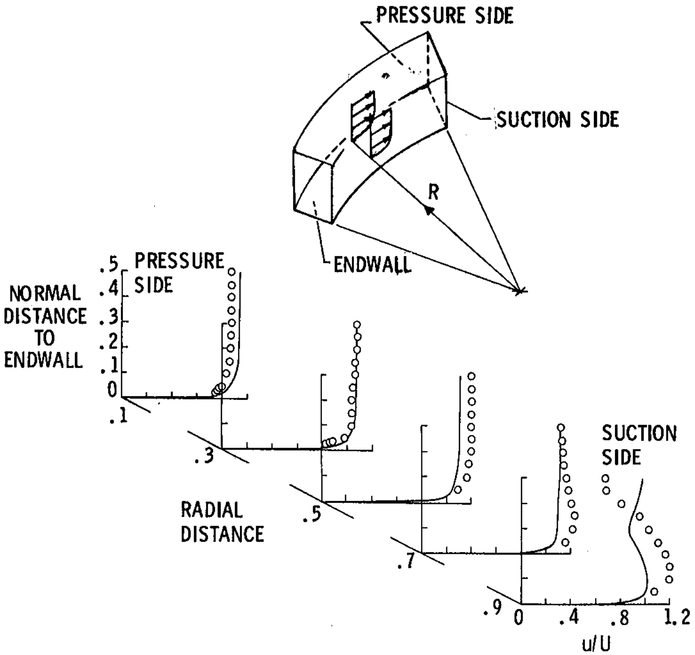


Figure 5. - Flow along endwall.

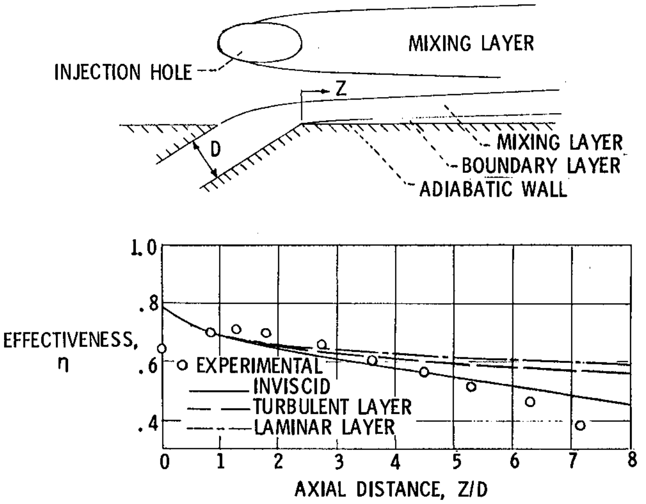


Figure 6. - Single-hole film cooling.

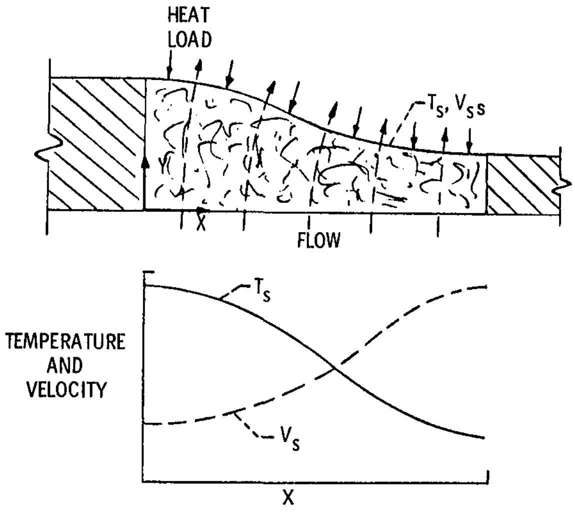


Figure 7. - Transpiration-cooled region.

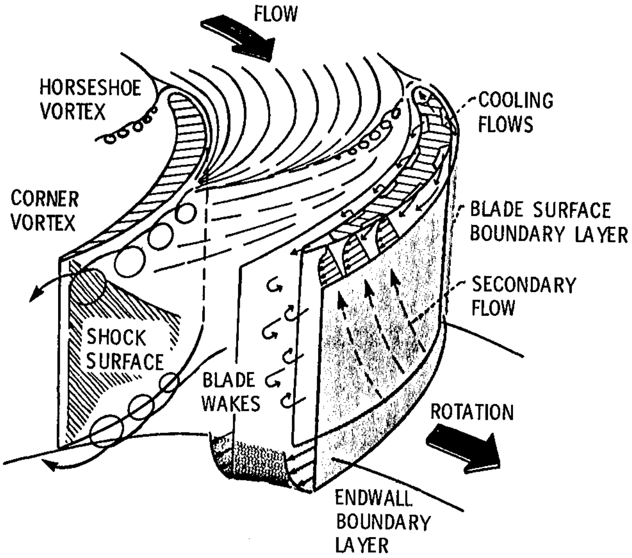


Figure 8. - Turbine blade row flow phenomena.

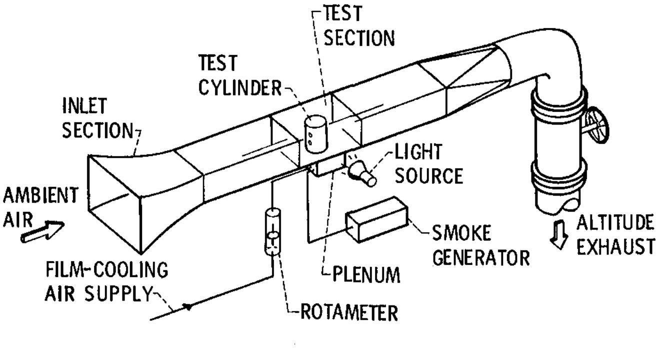


Figure 9. - Film-cooling flow visualization facility.

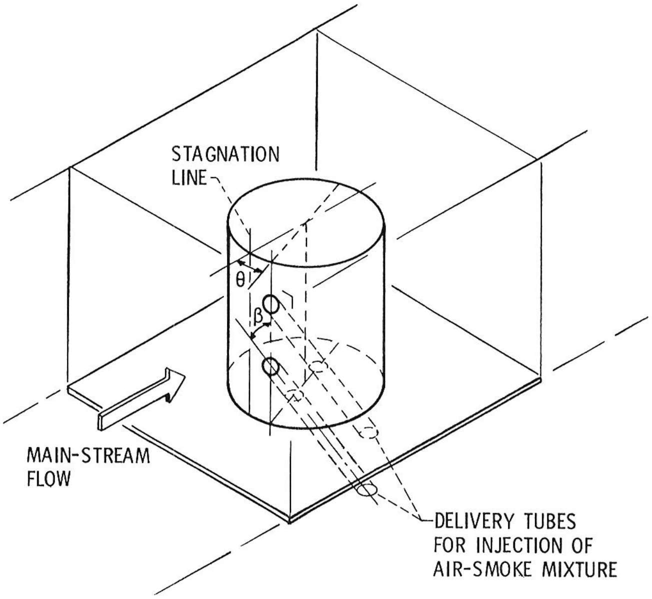


Figure 10. - Test section, where β is the injection angle relative to the surface and θ is the angular location from the stagnation line.

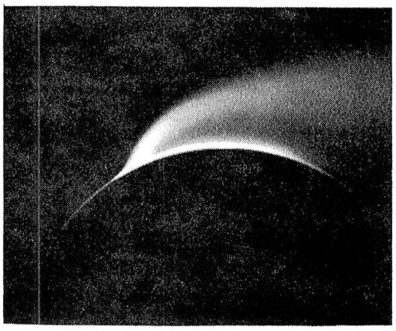


Figure 11. - Film injection of smoke over a cylinder in crossflows.

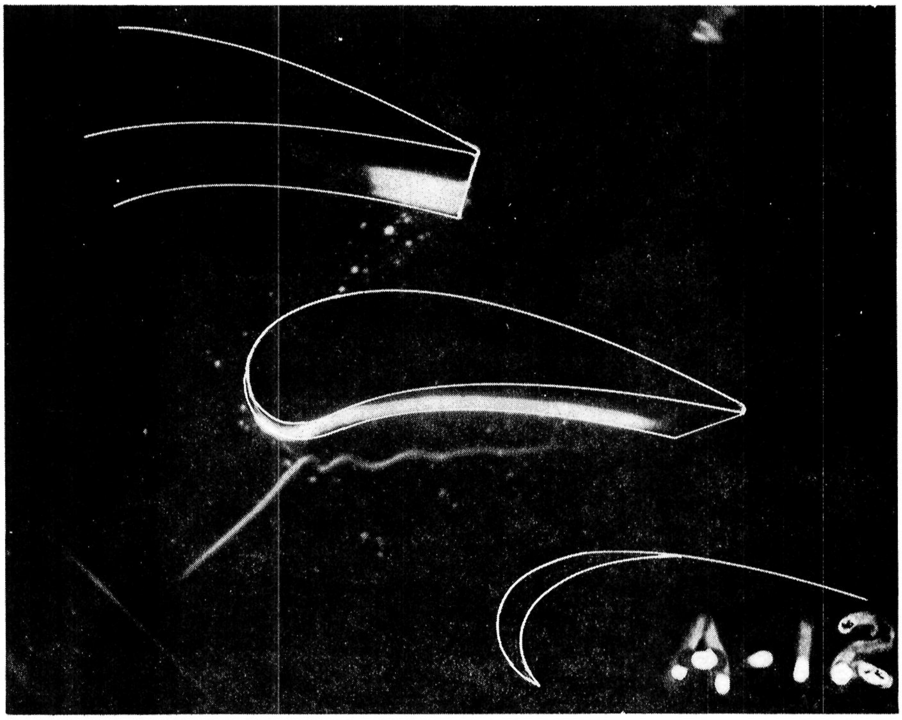


Figure 12. - Soap bubble visualization of horseshoe vortex.

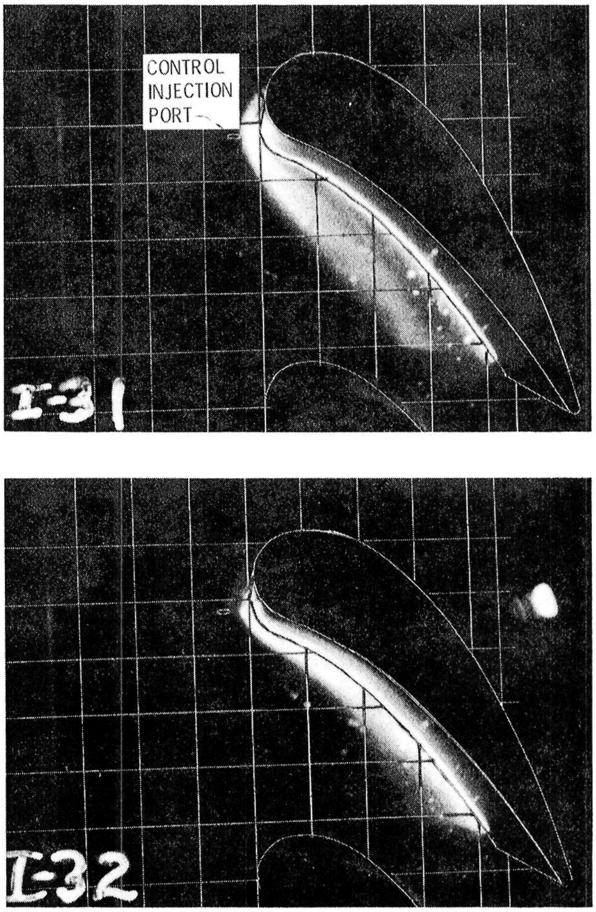


Figure 13. - Smoke visualization of effect of injection of air on horseshoe vortex.

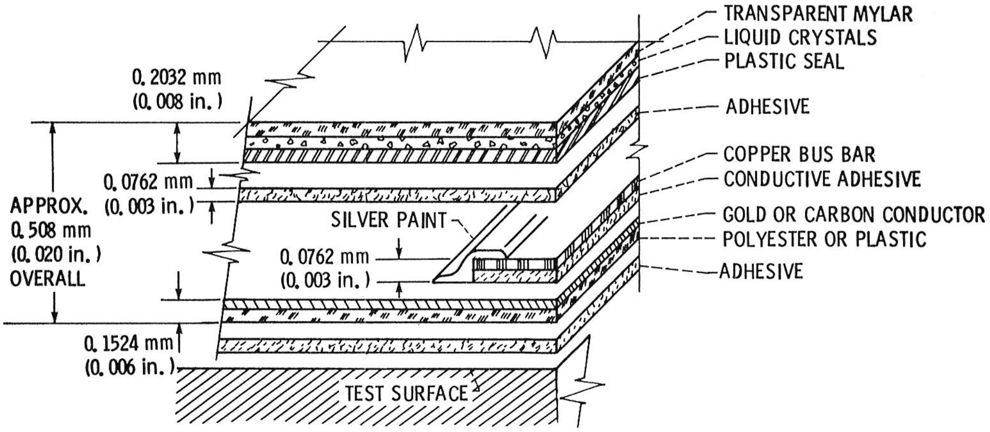


Figure 14. - Liquid-crystal sheet - electric heater composite (not to scale).

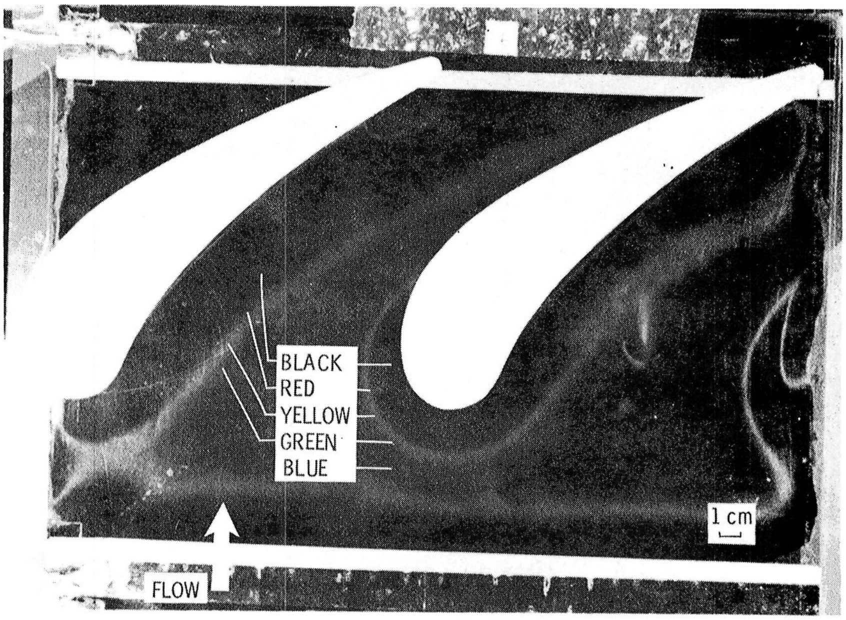
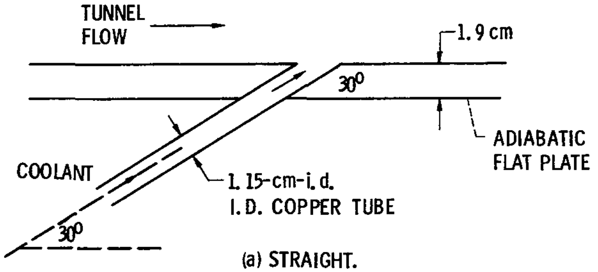
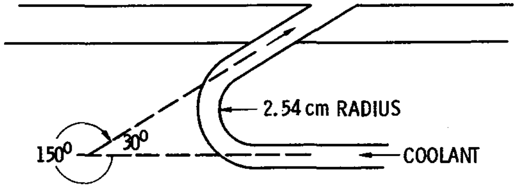


Figure 15. - Liquid-crystal visualization of isotherms on endwall of linear cascade.



(a) STRAIGHT.



(b) CURVED.

Figure 16. - Straight and curved film coolant-tube geometries.

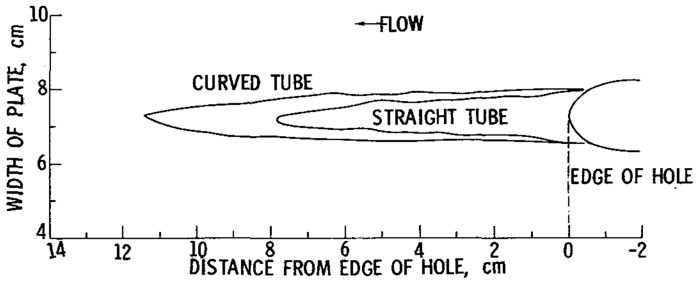


Figure 17. - Computer plot of actual-size isotherm trace, comparison of straight and curved tubes. Cooling effectiveness, 0.46; blowing rate, 0.46; free-stream velocity, 31.4 m/sec.

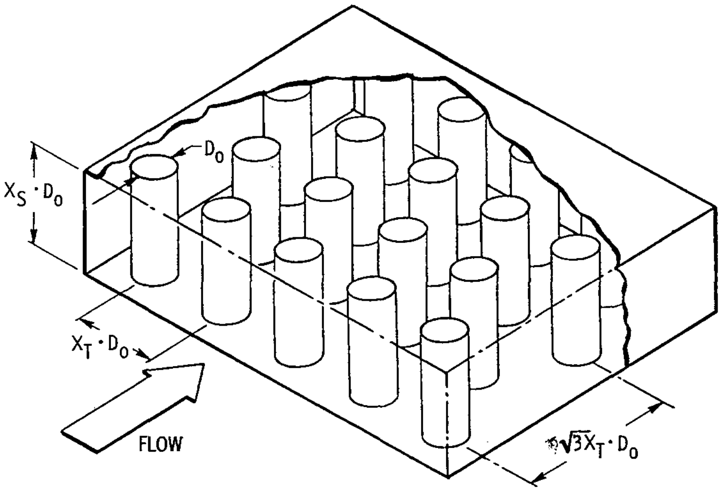


Figure 18. - Pin-fin channel geometry.

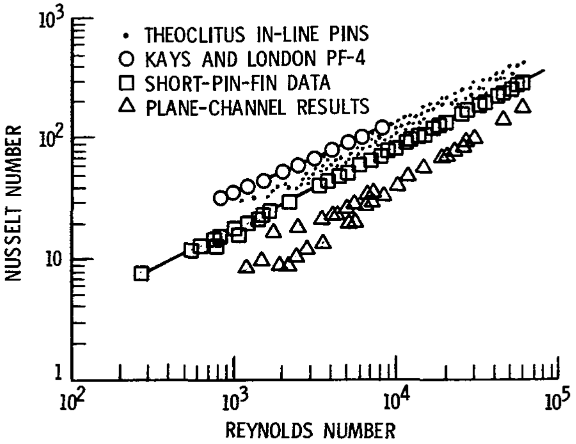


Figure 19. - Results of pin-fin heat transfer experiments.

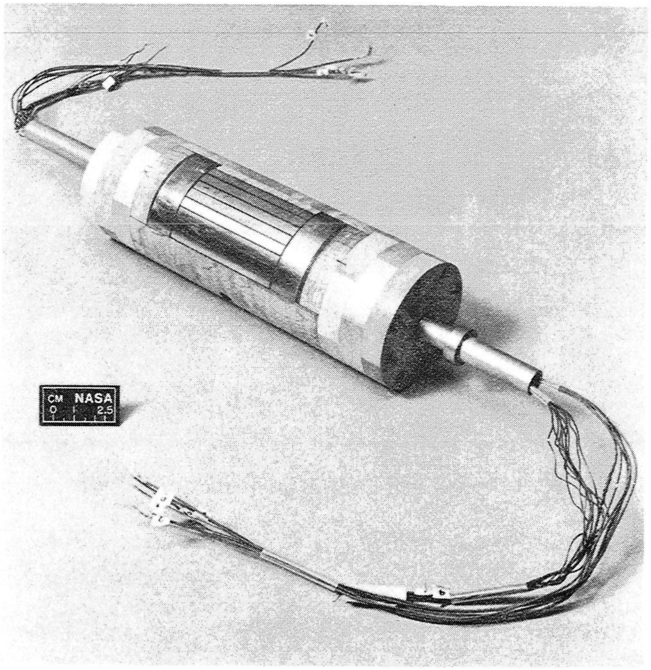


Figure 20. - Test section for circular-cylinder simulation of heat transfer to turbine blade leading edge.

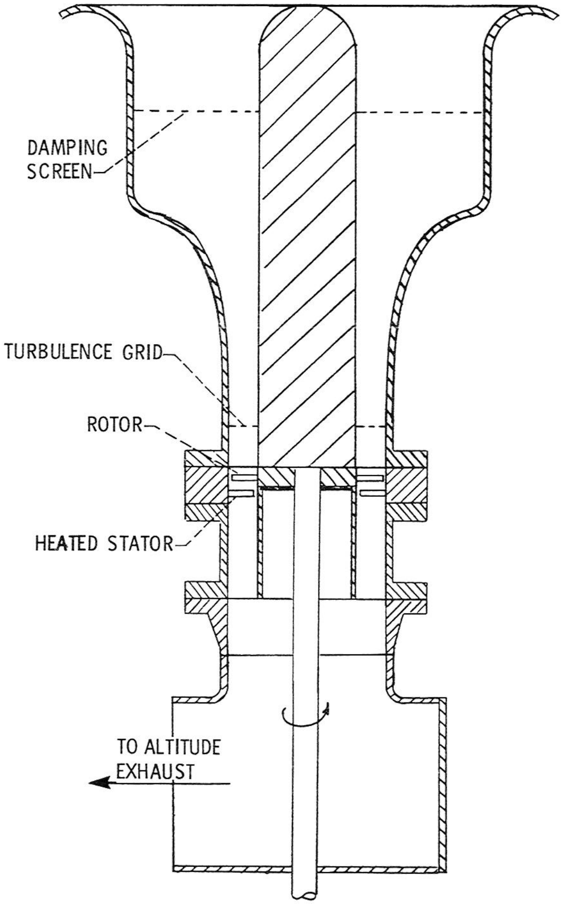


Figure 21. Heat transfer-in-rotor-wakes experiment - conceptual layout.

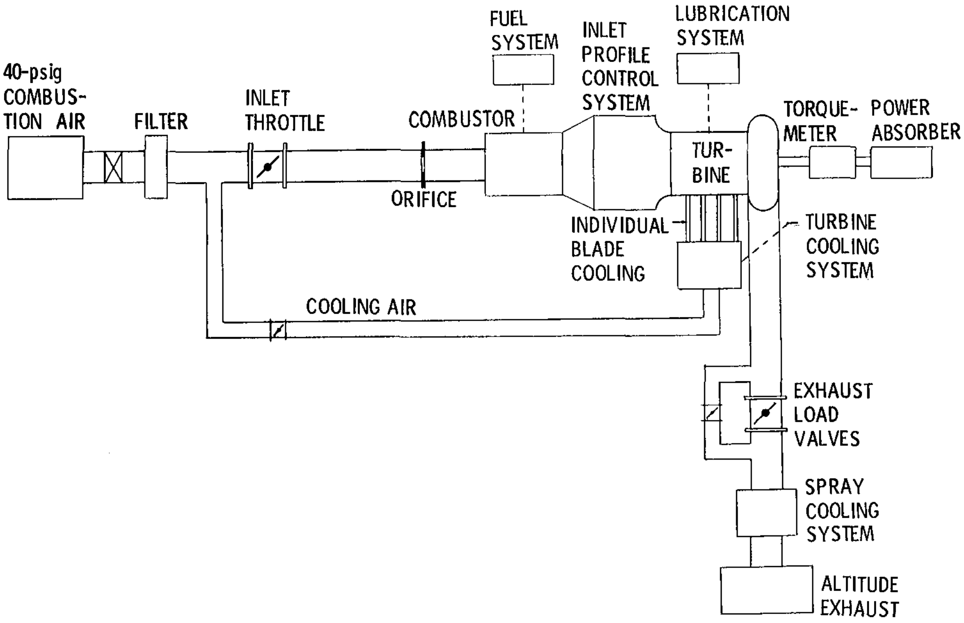


Figure 22. - Computational fluid mechanics verification facility - large, low-speed turbine.

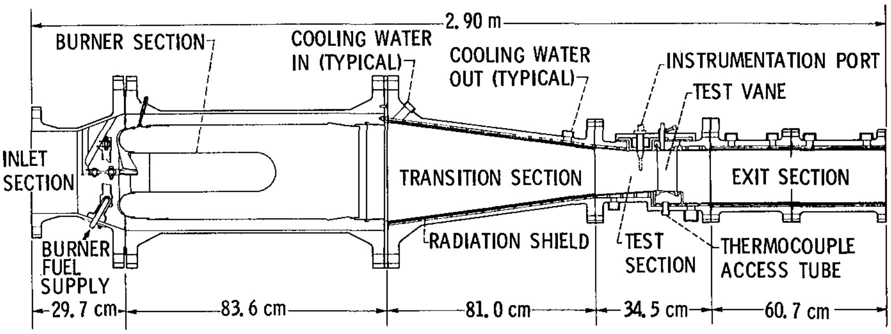


Figure 23. - J-75 cascade and flat-plate tunnel facility.

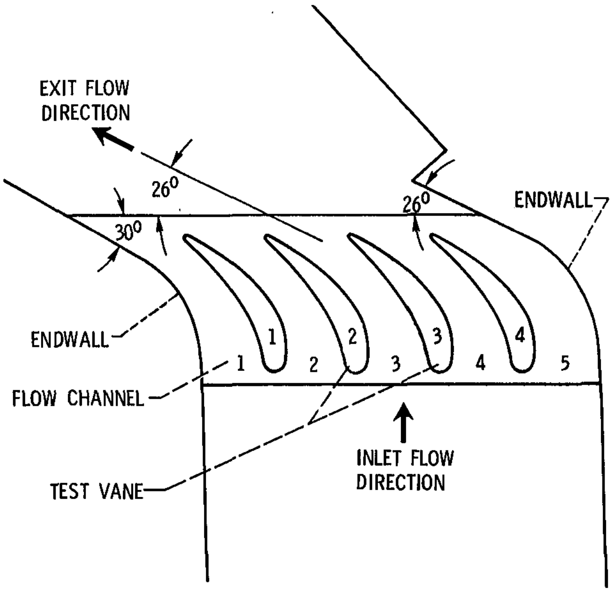


Figure 24. - Schematic of four-vane cascade test section.

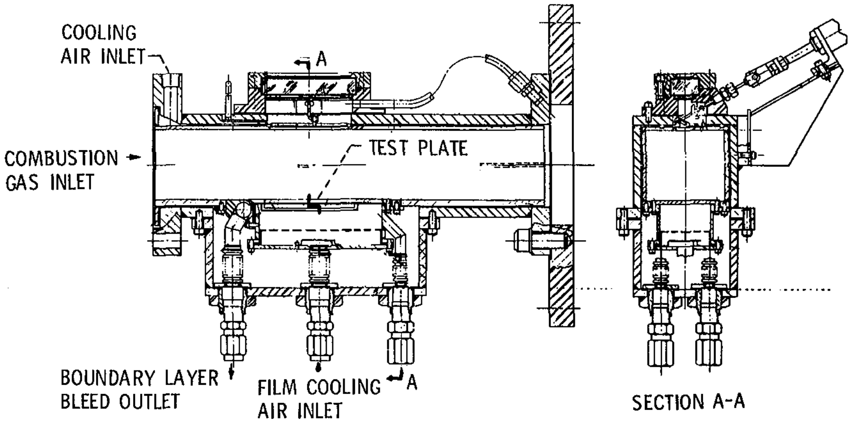


Figure 25. - Full-coverage-film-cooling facility.

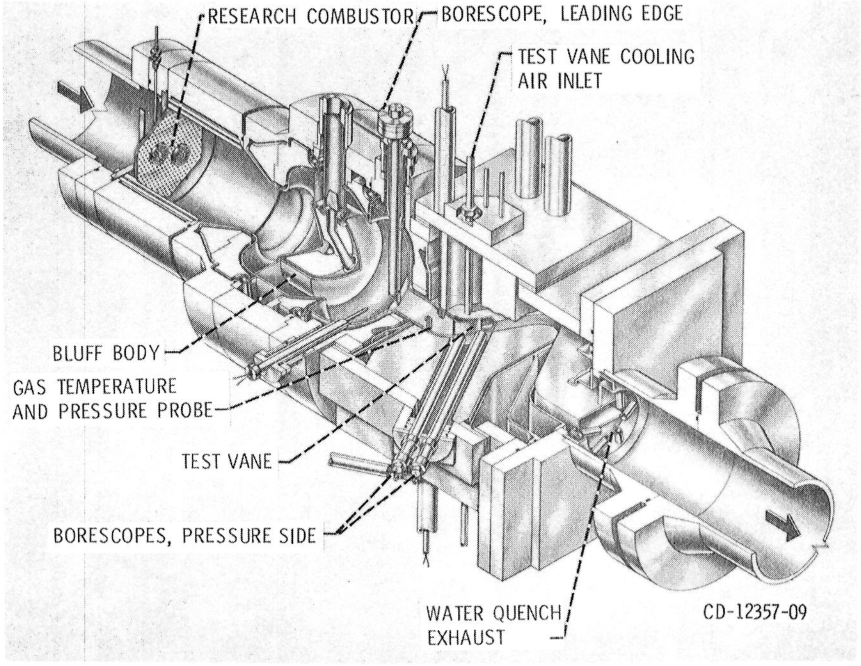


Figure 26. - Cutaway view of single-vane tunnel heat transfer test facility.

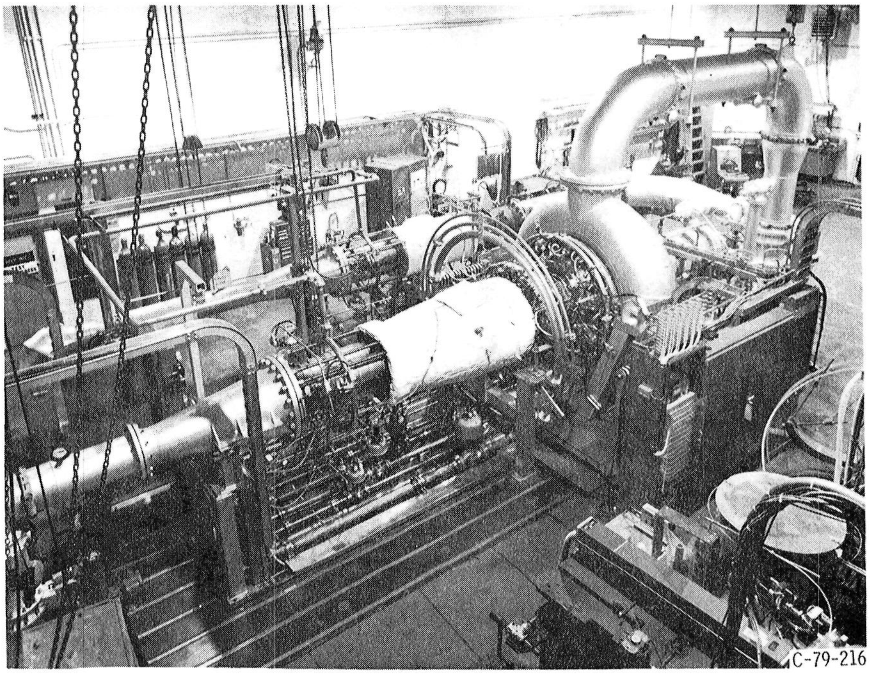


Figure 27. - Warm-core turbine facility.

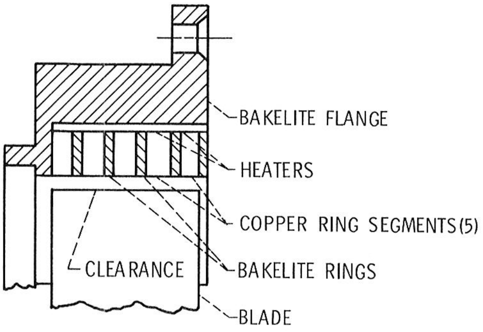


Figure 28. - Turbine shroud heat transfer test. $Nu = f(re, rpm, clearance, X_\ell)$.

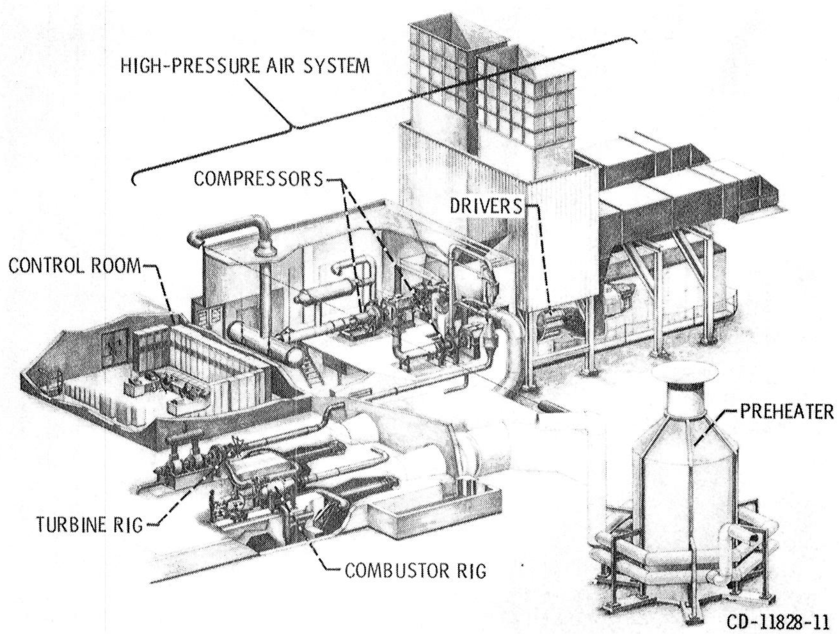


Figure 29. - High-pressure facility.

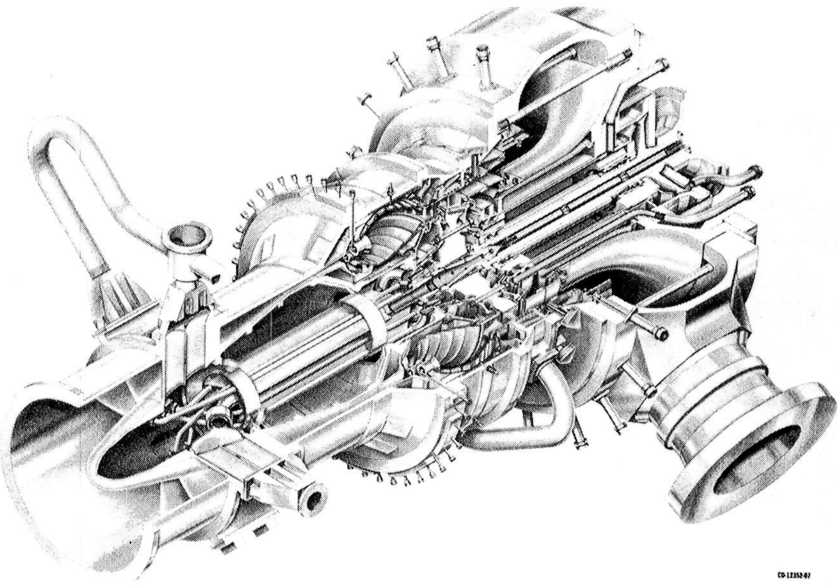


Figure 30. - High-pressure turbine.

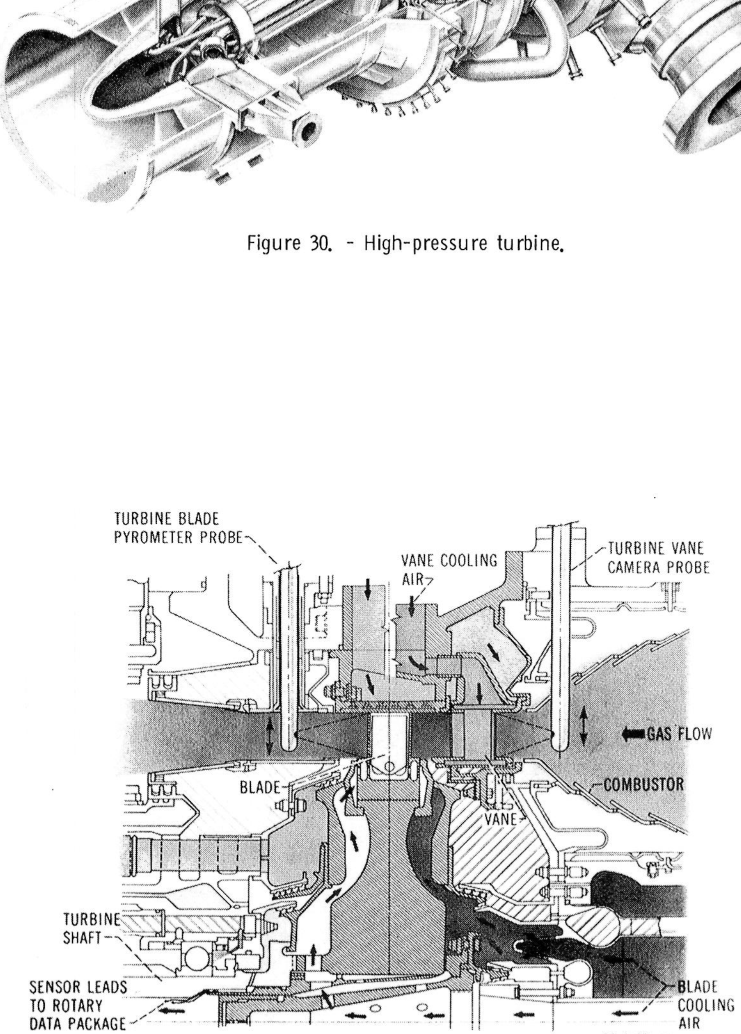


Figure 31. - Test section of turbine cooling rig.

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15. Supplementary Notes

16. Abstract

A two-day workshop on fundamental heat transfer research for gas turbine engines was held at the NASA Lewis Research Center on October 8 and 9, 1980. Thirty-seven experts from industry and the universities joined 24 Lewis staff members in an exchange of ideas on trends in aeropropulsion research and technology, basic analyses, computational analyses, basic experiments, near-engine-environment experiments, fundamental fluid mechanics and heat transfer, and hot-section technology. This proceedings, edited by Darryl E. Metzger of Arizona State University, summarizes the workshop.

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